UNIVERSITY OF CAPE TOWN
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Assessing the economic value of using structural health monitoring systems on South African bridges by studying the Ermelo-Richards Bay Freight Railway line.

By

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DEPARTMENT OF CIVIL ENGINEERING

Supervisor: Professor Pilate Moyo

25 April 2017

DECLARATION

I declare that: **Assessing the economic value of using structural health monitoring systems on South African bridges** is my own work and that all sources that are quoted have been referenced.

Signed by candidate

Keamogetswe Antoinette Mmekwa

25 April 2017

DEDICATION

To my friend Joe Maseko who passed on 22^{nd} January 2017 and was awarded his Masters posthumous. You may be gone, but your words of encouragement live on.

ACKNOWLEDGEMENTS

Firstly, I would like to thank God for the ability to fulfil my curiosity surrounding the advancement of infrastructure.

This dissertation is based on a research project of the use of Structural Health Monitoring systems on the Transnet Freight Rail coal line from Ermelo to Richards Bay. Permission to use the data obtained from Transnet Freight Rail (TFR) is gratefully acknowledged. The opinions expressed in this dissertation are those of the author and do not necessarily represent the policy of TFR. A special thanks to Mutshinya Netshidzati, personal assistant to Mr. Tshilidzi Munyai as well as Mr Munyai himself from TFR for assisting me in obtaining some of the data used in the case study which forms part of this research.

- I wish to express my gratitude towards my former employer PHB Engineers for sponsoring my studies, encouraging me to pursue my studies and for affording me the time away from work to attend classes.

- A thank you to my colleagues at the Consulting Engineers South Africa who have given me a platform to connect with the leaders in the infrastructure sector to assist in finding solutions to South Africa's infrastructure challenges.

- To my supervisor, Professor Pilate Moyo for his invaluable input and technical guidance.

- To my mother Kgabo Mmekwa for her unwavering support even while pursuing her own studies to obtain her PHD. THANK YOU Mom for always believing in me and pushing me to strive for more.

- Lastly, to the rest of my family and my friends for their patience, support and encouragement during my studies…thank you.

ABSTRACT

There is a need for appropriate tools and techniques to undertake the vast task of sound repair, maintenance and rehabilitation of concrete infrastructure, which is deemed to be deteriorating at unacceptable rates. Low economic growth predictions contribute to limited budgets and a deferring of maintenance. The use of technology could be used to extend the useful life of concrete structures.

Structural Health Monitoring Systems (SHMS) can be used to monitor structural integrity and the information obtained from these systems can be used in detecting overloading (on bridges for instance) and to alert asset managers of any due maintenance. Büyüköztürk (2007) argues that conventional methods of inspecting the condition of bridges are generally subjective and that this does not give a true reflection of the state of the structure.

The objective of this study is to determine the economic value of using SHMS on South African bridges as opposed to conventional bridge inspection methods. The detailed study was conducted on railway bridges on the Transnet Freight Rail (TFR) Ermelo - Richards Bay coal route to assess the contribution that a commodities line such as this one makes to the South African economy. This study makes use of data from Transnet to establish economic value. It is recommended that the results and recommendations be used for a more detailed study into the value of SHMS and for the study to be extrapolated for use on other types of bridges (e.g. road bridges).

TABLE OF CONTENTS

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ART	Active RF Test
BMS	Bridge Management System
CAR	Center for Automotive Research
COTO	Committee of Transport Officials
CSHMS	Civil Structural Health Monitoring Systems
CSIR	Council for Scientific and Industrial Research
ECSA	Engineering Council South Africa
EUL	Estimated Useful Life
GDP	Gross Domestic Product
LCC	Life Cycle Costing
MICA	Manual for Infrastructure Condition Assessment
MEMS	Micro-Electro-Mechanical-Systems
Mt	Million Tonnes
NEC	(The White House) National Economic Council
NPV	Net Present Value
PICC	Presidential Infrastructure Coordinating Committee
RBCT	Richards Bay Coal Terminal
RC	Reinforced Concrete
RUL	Remaining Useful Life
SAICE	South Africa Institution of Civil Engineering
SANRAL	South African National Roads Agency Limited
SHM	South Health Monitoring
SHMS	Structural Health Monitoring Systems
SIPs	Strategic Integrated Partnerships
SOE	State Owned Enterprises
TFR	Transnet Freight Rail
USA	United States of America
WLCC	Whole Life Cycle Costing
WNS	Wireless Network Systems

CHAPTER 1

1 INTRODUCTION

1.1 Background

Infrastructure investment in South Africa is a complex issue which involves delving into political issues, socio-economic issues as well as a low growth economy. Fourie (2006) suggests that in South Africa there is a political preference for providing new infrastructure rather than improving existing infrastructure. New infrastructure provides a wider voter support base and this can lead to significant inefficiencies (Fourie, 2006) with respect to the maintenance of existing infrastructure. Despite this assertion, it is a fact that infrastructure around the globe is ageing due to increased utilisation and a lack of financial resources for infrastructure maintenance. Smart structures could yield a solution to the global infrastructure challenge.

Smart structures is a concept that integrates various elements such as sensors, actuators, power sources, signal processors, and communications networks to sense and react to their environment in an expected and desired manner (Hurlebaus et al., 2014). They not only support or resist mechanical loads, but may also reduce vibration, mitigate acoustic noise, monitor their own integrity while in operation and throughout their lives, providing continuous information from the structure in its current environment. NEC (2014) state that the economic benefits of smart infrastructure investment are long-term competitiveness, productivity, innovation, lower costs, and higher incomes. However, the value of using smart structures, has not yet been determined. Structural Health Monitoring Systems (SHMS) which originate from the aircraft and space industries are a concept of smart structures that have been implemented on structures around the world for many years (Hurlebaus et al., 2014). One of the main advantages of SHMS is that real time, accurate information can be obtained from the structure to establish its actual condition. This is useful in deciding when maintenance should be conducted.

Investment in infrastructure in South Africa has declined in real terms since the 1960's (Perkins, 2011). Figure 1-1 illustrates this decline by showing a correlation between the investment in economic infrastructure and economic growth. South Africa like many countries around the world, faces the challenges of ageing infrastructure. The continuing demand for new infrastructure in the country means that there is a pressure on financial resource management and the maintenance of existing infrastructure is often not well resourced.

Rust and Koen (2011) suggest that there is a need to stimulate innovation in the construction industry to develop uniquely South African technological solutions required to provide and maintain economic and social infrastructure. Bridges constitute critical infrastructure for the social and economic development of communities and it is essential that they are maintained. It therefore brings forth the question on whether current bridge management systems are effective in dealing with the prioritising of defective structures or whether there is any economic value in investing in SHMS, which give more accurate information.

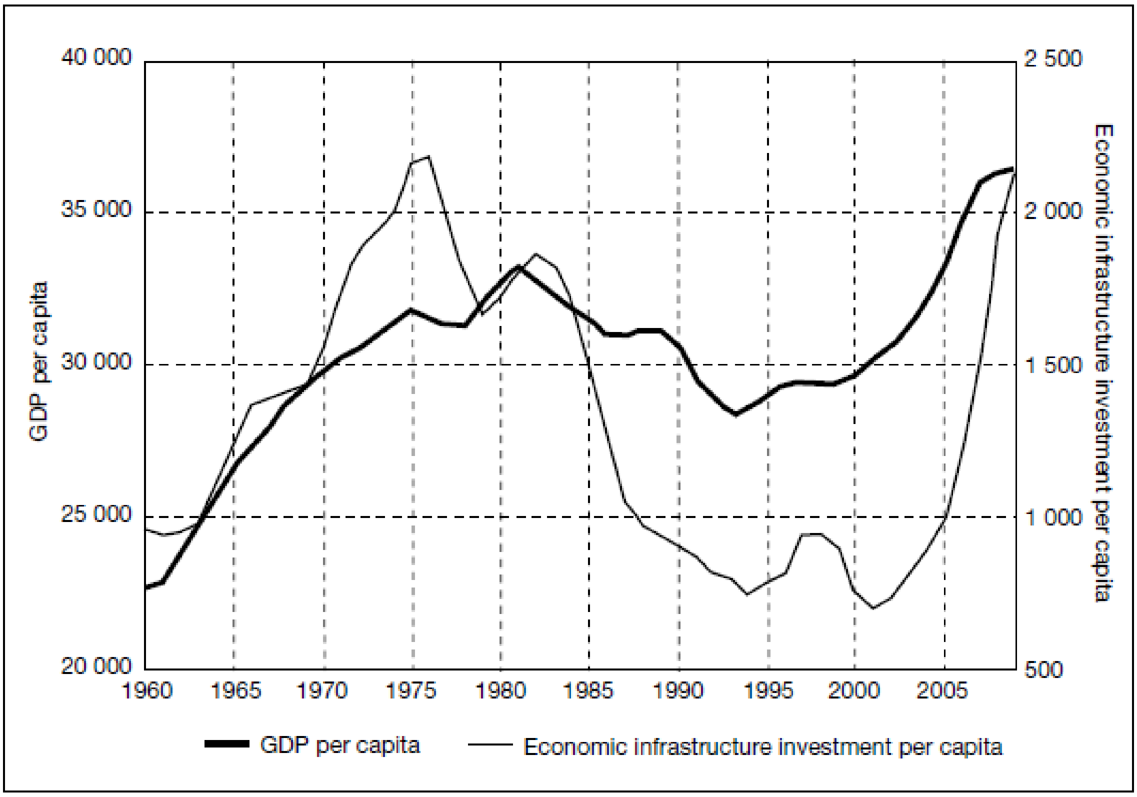


FIGURE 1-1: (South Africa) Real GDP and public – sector infrastructural investment, per capita, Rands, 2005 prices, moving average (Source: Perkins, 2011).

1.2 Problem Statement

Structures are constantly subject to movement and increased deterioration due to: vibration, deflection and the alteration of material properties by temperature variations and other environmental conditions. This movement is seldom visible to the naked eye and sometimes sensors are introduced to detect local and global movements as well as deflections.

Sensors monitor movement for a period of time (sometimes for the life span of the structure) and the data collected are used to identify signs of degradation. Although this is useful, it is also important to understand what is going on within the structure, which is something that is overlooked by visual inspections which only rely on the appearance of the structural system to make a conclusion on its integrity.

Internally, sensors are able to detect defects such as corrosion, which can be the main cause of deterioration in a structure. The ability to determine whether damage is caused by reinforcement corrosion, fatigue or other defects helps to determine what repairs should be conducted that will extend the life cycle of the structure and keep it in a safe operating condition at a minimal cost and maximum sustainability. Although the multitude of sensors and the data monitoring service may come at a high cost, there needs to be a cost comparison made on how these sensors fare against the cost of doing unnecessary or ineffective routine maintenance. Moreover, maintenance is sometimes conducted too late when the structure is in a critical condition. Currently, it is not standard practice in South Africa to have monitoring systems embedded within bridges or other structures. When monitoring systems are used, it is often as a response to a query on the integrity of a bridge or other structural system.

1.3 Research objectives and Questions

The main objective of this research is to assess the economic value of using SHMS as a tool for the continuous structural monitoring of railway bridges. SHMS could in future supersede visual inspections, as they provide information that is not visible to the naked eye. This eliminates the complete reliance on visual inspections by providing more accurate information that will ensure that structures remain in a safe-to-use condition. While maintenance is often deferred, SHMS ensure that when an alert is made to an asset manager, they know how to prioritise the remedial action required on the structures and which structures require attention more urgently. This research consists of a literature review, a case study, a cost analysis and an assessment of the economic value of SHMS. This study aims to address the challenges of condition assessments that come with current bridge management techniques. It seeks to identify the most effective, sustainable solution for the safe monitoring of bridges. With the aid of a case study, it considers the viability of introducing Structural Health Monitoring Systems on South African bridges by assessing their economic value.

The findings aim to establish whether the cost of the implementation of SHMS on South African bridges would be more cost-effective than bridge inspection costs which are associated with various BMSs. It also considers the most beneficial use of SHMS: As a monitoring tool on existing structures or best used as an inspection tool embedded in-situ within structures to determine the true life cycle of structures.

The research questions to be addressed are:

i) To what extent are current BMSs effective in the safe monitoring of structures?

ii) Are the current methods of routine maintenance effective in ensuring that structures remain in a safe-to-use condition?

iii) Can BMS in its current format ever fully be disposed of and replaced by technology?

iv) What constitutes economic value of SHMS?

v) Is there space for autonomous devices in the industry as a means of bridge management?

1.4 Scope and limitations

The scope entails taking a look at the future of bridge monitoring and whether BMSs as currently used are sustainable based on the level of maintenance that is being conducted. Technologies such as SHMS provide more accurate information on the condition of structures thereby making preventative maintenance an option even when budgets are constrained. However, their value has not yet been assessed. Economic value is a measure of benefit provided by goods or services. Short and long term benefits are explored in the study. The limitations of the study are as follows:

- The study period for bridges is limited to exploring the future of BMS in the next 40 years.
- With real time accurate information of structures, SHMS may provide information on whether current life cycle models are still valid. The validity of the models do not form part of the scope of this research.
- As the most critical part of the coal line, the research has been limited to the case study of the Ermelo to Richards Bay railway line. Other commodities are transported on this line, but are not used in the case study.
- To determine a loss of income based on delays caused by bottlenecks requires a traffic study to be conducted. The cause of loss is only based on replacement due to complete failure.
- Value in the case study is limited to the economic importance of bridges such as those on the coal line in the micro economic sense, socio-economic value has not been considered.
- Value in the study is also limited to the negative impact that *BMS visual inspections* have on bridge management in the long term if SHMS are not installed.
- Maintenance records of the bridges could not be obtained, thus the condition is based on the expected design condition for the respective ages of the bridges and the service life cycle models.
- The initial construction cost records could not be obtained. Thus the costs of the bridges are based on replacement using the most cost-effective bridge system.

1.5 Organisation of the dissertation

CHAPTER 1 - Serves as an introduction and to provide a background on the research and the significance of conducting this research.

CHAPTER 2 - A literature review of BMS and SHMS.

CHAPTER 3 - Explores the economic value of SHMS.

CHAPTER 4 - Describes the research methodology that is used.

CHAPTER 5 - A Case Study of the Transnet Freight Rail Coal line.

CHAPTER 6 - Cost Analysis and Discussion.

CHAPTER 7 - Conclusions and Recommendations.

CHAPTER 2

2 LITERATURE REVIEW

2.1 Introduction

Bridges are transport structures that are designed to provide a link over geographical or manmade features, but also to carry traffic and people safely. Their social purpose is complex and closely linked to their economic, financial and aesthetic functions. Their financial purposes may include the economic benefit for an area such as when generating income for a country for the facilitation of exports. Thus the consequences of not fulfilling their economic, financial and aesthetic functions could affect their social purpose. Bridges cost money to build and maintain and may also have a direct impact on the economy of a region or country as they serve as direct links to major ports.

The literature review explores the various types of bridges, bridge components and bridge management. It evaluates current BMSs from various research reviews, explores the reviews on SHMS, it looks at bridge costing, the importance of bridges and the infrastructure challenge that South Africa faces.

2.1.1 Bridges

In order for a structure to be classified as a bridge, it must satisfy one or more of the following criteria (COTO, 2016a):

- Any single span > 6m;
- Individual clear spans exceed 1.5m and overall length measured between abutment faces exceeds 20m; or
- The open height is equal to or greater than 6m; or
- The total cross sectional opening is equal to or greater than $36m^2$
- The structure is a road-over-rail, rail-over-river, rail-over-road, etc. structure, even if the maximum span is less than 6m.

A general bridge is defined as a structure that consists of separate and clearly identifiable elements such as deck slabs, deck expansion joints, abutments, piers and foundation footings. Elements such as invert slabs; cut-off walls are normally not present. The concrete deck is usually used as a roadway (COTO, 2016a).

The various components of a general bridge are shown in Figure 2-1:

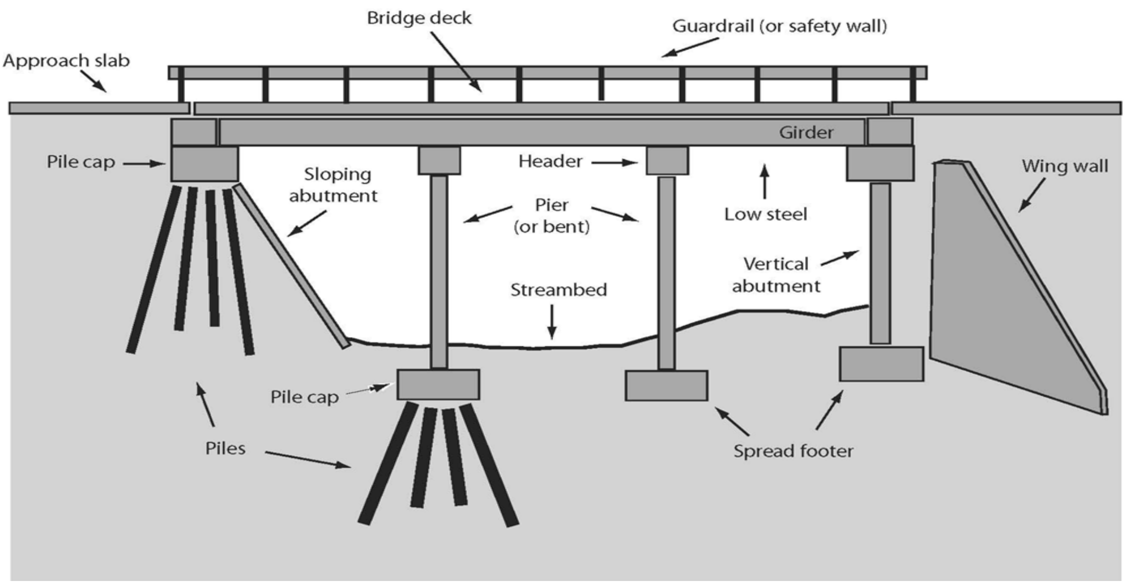


FIGURE 2-1: Bridge (General) Components (Source: www.civilarc.com)

All bridges contain three main components, namely: The superstructure, bearings and the sub-structure, (Figure 2-1). The components of a bridge are described in Table 1 (COTO, 2016a):

TABLE 1: Bridge Components (Source: Mbanjwa, 2014)

Bridge Component	Description
Superstructure	The component of the bridge that carries the load which is the roadbed is the substructure (i.e. roadbed, truss or girder etc.). It then transfers the load to the substructure and thereafter, the ground. The substructure is the roadbed, truss or girder, etc.
Bearings	The bearings are components that ensure that the dead and live loads and are evenly distributed and transferred to the substructure.
Substructure	The substructure refers to the component of the structure that transfers the loads to the ground. This includes the abutments, piers, wing walls, foundations etc.

One of the four types of bridges, Bridge (General) in the bridge asset class has already been discussed in 2.1.1 and shown in Figure 2-1. The other types are: Arch Bridge (Figure 2-2), Cable Bridges and a Bridge cellular. Arch bridges were mostly built in an era when both architecture and purpose played a pivotal role. However, budget constraints in recent years have for the most part resulted in the most cost effective solutions being prioritised over architectural aspects. Today, replacement systems for a bridge are based on the guidelines below. They are used in establishing the most cost effective bridge solutions:

For a deck span of 6-15m the most economical solution is a solid deck, from 15 to 30m, pre-cast beams and from 30m to 500m, a box girder would be most preferable. The costs/m^2 are discussed in Chapter 4. There are many variables that constitute the total value of a bridge; therefore, the costs/m^2 are used only as a high level estimate.

2.1.1 Bridge Types

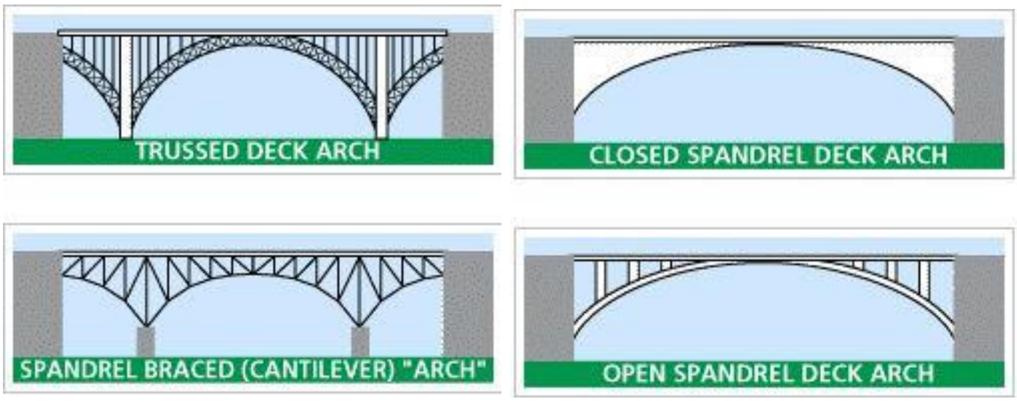


FIGURE 2-2: Spandrel Arch Bridges (Source: globalsecurities.org)

a) Arch Bridge: An arch bridge type structure includes solid spandrel filled arches; open ribbed spandrel arches; and open spandrel arches (COTO, 2016b).

b) Cable bridges: A cable bridge type structure includes suspension bridges; cable stayed bridges and extra dosed bridges (COTO, 2016b).

c) Cellular bridges: This is a bridge structure consisting of “cellular” units. A cellular unit can typically be described as an “opening” where, in general, the overall cell length is greater than the cell width. Elements such as separate deck slabs, abutments/piers, foundations, etc. are not clearly identifiable while elements such as invert slabs, apron slabs, cut-off walls etc. are normally present (COTO, 2016b).

2.1.2 Bridge Spans

The spans of a bridge are the distances between supports. Supports can be in the form of a pier, beams or abutment. The various spans simple, continuous, cantilever and cantilever (with suspended spans) are shown in Figure 2-3 below:

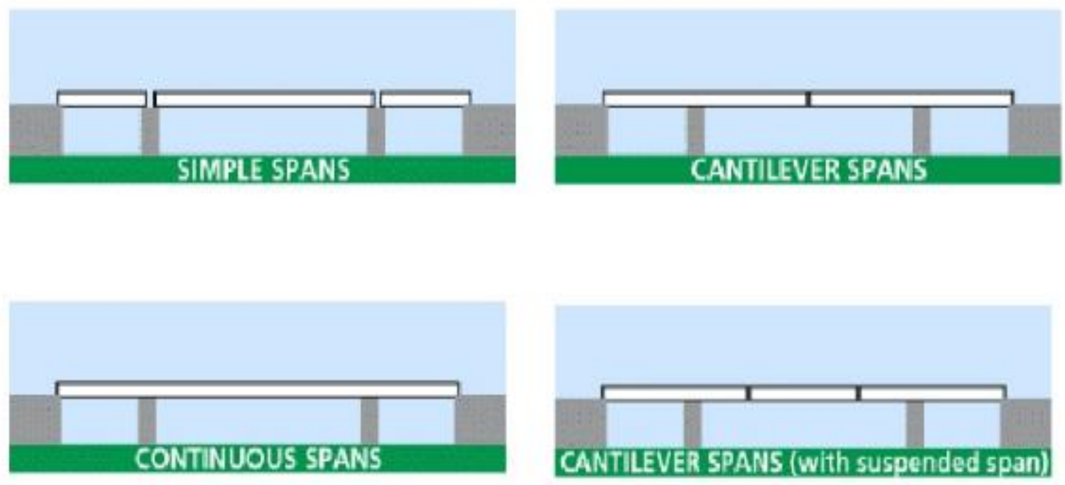


FIGURE 2-3: Bridge Spans (Source: globalsecurities.org)

a) Simply Supported: Beam bridges are the most common type of bridge. If beams are supported by two supports, on piers or columns, they are deemed simply supported. The vertical forces on the bridge become shear and flexural loads on the beam and are transferred down its length to its piers or columns.

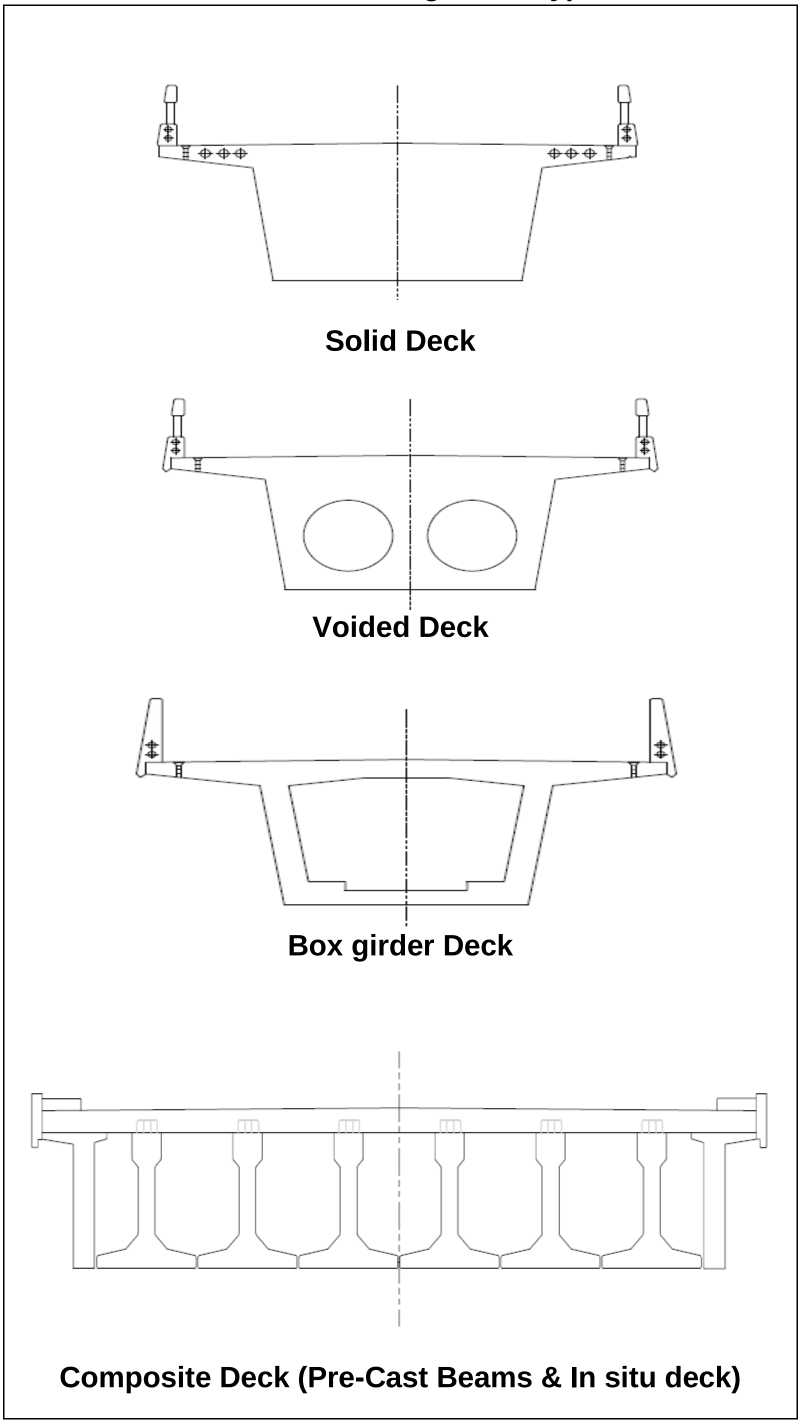
b) Continuously Supported: If two or more beams are joined rigidly and extend over more than two supports, the beam bridge is considered a continuous beam bridge. Both tension and compression forces on the top and bottom of the beam are transferred from the beam to the ground via the sub-structure.

c) Cantilever Bridge: Cantilever bridges usually have two beams supporting another beam that is supported by piers or columns. The dead and live loads of the bridge are borne by the two outermost piers and then transferred to the ground through these piers. This beam is usually the vehicle roadway and is composed of reinforced concrete.

2.1.3 Bridge Deck Systems (Concrete)

There are various types of bridge systems for the loads, span lengths and the construction method that are being proposed. Shown in Figure 2-4 are four different bridge deck types: Solid deck, a voided deck, box girder deck (Pre tensioned/post tensioned/incrementally launched) and a composite deck (with pre cast beams and a slab cast in-situ).

FIGURE 2-4: Bridge deck types



2.2 A Bridge Management Systems (BMS) current status

The goal of infrastructure asset management is to meet a required level of service in the most cost effective way for present and future customers (Mc Donald, 2013). This is what Bridge Management Systems (BMS) aim to do for the safety monitoring of bridges by means of routine inspections throughout their lifecycle. BMS is a comprehensive approach to bridge management which encompasses the convergence of disciplines of structural engineering, operations research, economics, planning and information technology (Hearn, et al., 2000). For the purposes of this study however, unless explicitly differentiated to illustrate a point, BMS refers to the current manual methods of data collection by conducting on site routine visual inspections of bridges by a qualified bridge inspector.

Routine inspections consist of observations and/or measurements needed to determine the physical and functional condition of bridges, to identify any changes from initial or previously recorded conditions and to ensure that the structure continues to satisfy present service requirements (Hearn, 2007). However, BMS's do fall short of achieving their objective when remedial actions are not pursued and ratings are not conducted accurately. BMSs have been used by asset managers, and over the years the systems have improved with some transitioning into electronic systems, however they are still heavily reliant on human intervention.

On the other hand, while Structural Health Monitoring Systems (SHMS) have also been in existence for many years, they have not been implemented in the mainstream as a tool for replacing the current means of data collection and visual inspection methods used by traditional BMSs. The value of these systems is evident from the purpose that they serve and also given the vast amount of information that is attainable from these systems. The question on whether there is any economic value in using them on South African bridges has not been fully assessed.

A review on both BMS and SHMS is provided:

2.2.1 A review of bridge management systems

Roux et al. (2010) conducted a review on the Namibian BMS and other management systems. The South African National Roads Agency Limited (SANRAL) uses the STRUMAN BMS which is also used by other road authorities in Botswana, Swaziland and Taiwan. It was developed by the Council for Scientific and Industrial Research (CSIR) and makes use of a 4 point DERU (Degree, Extent, Relevancy and Urgency) rating system for observed defects (Roux et al, 2010). The system is heavily reliant on the experience and training of the bridge inspector. In order to utilise the system, consultants undergo a training course on the assessment methodology.

Roux et al. (2010) believe that the implementation of the STRUMAN BMS into the Namibian Road Authority has been effective in managing the structures on the authority's road network. This management tool has been cited as being useful in compiling an inventory of all bridges, major and minor culverts and to determine their condition in the process. In doing so it is believed that it is easier to budget for maintenance, repair and rehabilitation.

Some challenges are expressed by Roux et al. (2010) in the review. These include the visual assessment of the structure, the cost of collecting data, the accuracy in capturing the data, analysis and a prerequisite of having an inventory of all the structures to be inspected. The inventory would indicate the structure type, class, the size of the structure, where it is located and some general information on the structures. Other challenges may include not having access to a particular site due to its geographical location or general access issues e.g. if the entrance is located on private property. These structures are often omitted in inspections and put off until the logistics are sorted out. The experience of the inspectors was also flagged as a possible reason for inaccurate ratings of the structural defects.

The challenges are echoed by Humphries (2013) who summarises in a review that inspectors tend to be overly conservative when they lack the experience of inspecting bad bridges; that insufficient thought and observation during the inspection of the defects results in some items not being rated important enough. A lack of understanding is also highlighted in this summary; that ratings should be based on how a particular element fulfils its function and not the element in relation to the bridge. In essence that experience is critical for BMS.

In South Africa the age gap of engineers and the experience required to be a bridge inspector could change the costs of bridge inspections over the years. Moyo and Alexander (2006) argue that a major concern in South Africa is the loss of experienced professionals to other countries. They note that despite the growing number of ECSA registered young professionals most of them do not have the necessary experience in bridge management and condition assessment. As a result, this puts pressure on the few bridge inspectors and leaves little time and resources for the training of young engineers. According to the Engineering Council of South Africa (ECSA), the National Engineering Skills Survey that was conducted in December 2013, the average age of an engineering professional in South Africa is 38 years.

The grouping is as follows:

Younger than 30 years: 27%

Between 30 and 50: 44%

Older than 50 years: 29%

The requirements to be a bridge inspector for SANRAL is shown in Table 2:

TABLE 2: Inspection personnel experience requirements (Source: Hearn, 2007).

Title	Experience (years)
Inspection Program Manager	17
Senior Bridge Inspector	17
Bridge Inspector	5
Major Culvert Inspector	5
Inspection Specialists	17

Over and above the criteria shown in Table 2, the inspectors must attend a two-day workshop run by SANRAL, in which the management system is outlined. In addition to this, inspectors are mandated to attend an inspection workshop and to provide a résumé detailing qualifications and experience (Hearn, 2007). The following requirements are compulsory: Professional Registration, a minimum 5 years of full time experience in bridges and bridge design and documentation.

Transnet Freight Rail (TFR) uses what is called a MICA system of inspection. MICA is a 'Manual for Infrastructure Condition Assessment' which is conducted by the Depot Engineer or a delegate of the Depot Engineer. The principle and exception list inspection is conducted by the Senior Bridge Engineer or a delegate of the engineer. According to MICA, an annual bridge, footbridge and pedestrian subway inspection shall be done. Throughout the year the engineers and technical staff are required to be alert and vigilant to detect any defects seen on the bridges and report such immediately to the central office. Exception list inspections are conducted by the central office based on exception lists from depots annually after the end of April. The manual details that the central office shall do principal bridge inspections at least once every five years. This inspection system is also heavily reliant on visual inspections.

Lessons learnt following an inspection for the repair of Bridge IB42 over the Limpopo River by Kruger and Humphries (2008) highlighted the importance of acting immediately when severe problems are encountered, especially when the safety of the public is at risk. Failure is defined by the FHWA (2011) as the inability of a bridge or one of its primary load-carrying components to perform its intended function. Furthermore, Kruger and Humphries (2008) emphasise understanding and determining the root cause of failure and to make sure that the repair solution addresses this problem. They highlight the importance of reinforcement detailing, the importance of regular bridge inspections and to endeavour to keep the original aesthetic character of old structures intact when repair work is undertaken.

Much of the advice given by Kruger and Humphries (2008) is seldom adopted. When bridge inspections are conducted the remedial actions are given a priority ranking and only those 'perceived' (given the subjective nature of condition assessment) to be most critical, are recommended for repair. When budgets are constrained, this becomes a problem as only a smaller group of 'critical' structures are considered. This is evidenced in the same items not having undergone rehabilitation despite the repeated recommendations over the years.

A field inspection sheet from the SANRAL BMS is shown in Figure 2-5. This makes use of a DERU rating system, which measures the degree of defects, the extent, the relevance of the defect and the urgency of the required repairs. The inventory photo report is shown in Figure 2-6. The MICA inspection for bridges measures defects using a grading of 1 to 4 where 1 represents ‘Good’, 2 indicates that the structure is in need of ‘minor repairs’ and/or can be ignored, 3 indicates that the defect should be addressed during planned maintenance and 4 is a rating given for structures in need of immediate or emergency repair work. This is recorded on a BBC8226 railway infrastructure asset condition assessment document for concrete bridges. The MICA inspection is conducted annually and whereas SANRAL conducts its inspections every five years. The BBC8226 form can be found in Appendix B.

BRIDGE MANAGEMENT SYSTEM

Field Inspection Sheet - BRIDGE

Structure No. :	N006_		
Structure Name :			
GPS/GIS :	Start	Middle	End
Latitude :	32d 41m 37.50s		27d 34m 25.20s
Longitude :	32d 41m 36.20s		27d 34m 28.70s

Current Inspection	Inspector	Firm	Date
Principal X Monitor		VKE Engineers	2016/06/08
Prev. Principle Inspection :		Vela VKE Consulting Engineers	2006/03/22
Last Monitoring Inspection :			

Route / Section :
Route km : 51.90
Other Bridge No. : 5638
N Route Over / Under : Over
Feature Road Name :
Feature Road No. :

Min. Vertical: Pos	S2				
Min. Vertical: (m)	5.30				
Direction of River Flow :	N/A				

Structure Type : Continuous
Year Constructed : 1985
Structure Orientation : North/South
OCI : 89.37
No. of Spans : 3
Overall Length : 88
Angle of Skew : 60

Inventory : Inspection : Reporting : Capturing :

N006_01N_B5638 : Komga Road

VARIOUS INSPECTION ITEMS

Inspection Item	D	E	R	Inspection Item	D	E	R	Inspection Item	D	E	R
1. Approach Embankment				5. Abutment Foundations				9. Superstructure Drainage			
2. Guardrail				6. Abutments				10. Kerbs/Sidewalks			
3. Waterway				7. Wing/Retaining Walls				11. Parapet			
4. Approach Embankment Protection Works				8. Surfacing				21. Miscellaneous Items			

N006_01N_B5638 : Komga Road

SUPPORTS							**SPANS**			
Inspection Item	12. Pier Protection Works	13. Pier Foundations	14. Piers and Columns	15. Bearings	16.Support Drainage	17. Expansion Joints	Inspection Item	18. Long Members	19. Transverse Members	20. Decks and Slabs
Supports	D E R	D E R	D E R	D E R	D E R	D E R	Spans	D E R	D E R	D E R

N006_01N_B5638 : Komga Road

WORK DONE

Item	Pos	Activity Code or Description	Quantity	Unit	Urgency	Make Safe	Remarks	Photo Report	Monitor Frequency

COMMENTS : N006_01N_B5638 : Komga Road

Further Inspection Needed ? Y/N	No	Further Inspection Needed ? Y/N
Was UBIU used ? Y/N	No	Then please indicate any special requirements ie. 6m
Is UBIU needed for further Insp's? Y/N	No	Ladder, Bush Cutting, UBIU, better weather etc. If nothing then please state "none".

DERU Rating

D - DEGREE							E - EXTENT				R - RELEVANCY				U - URGENCY					
NA	UA Insp	None	Minor	Fair	Poor	Severe	Local	>Local	<Gnl	General	Min	Moderate	Major	Critical	Record	Monitor	Routine	10 yrs	< 5 yrs	ASAP
X	U	0	1	2	3	4	1	2	3	4	1	2	3	4	R	0	1	2	3	4

Structure No. : Page 1 of 2

Structure Name :

Insp. Date : Report produced on - 6/29/2016 10:19:22 AM

FIGURE 2-5: BMS - Field inspection sheet (Source: SANRAL BMS)

BRIDGE MANAGEMENT SYSTEM

Inventory Photo Report

Structure ID :

Structure Name :

Report produced on - 6/29/2016 10:15:59 AM

Photo Direction - W

Date of Photo - 3/22/2006 12:00:00 AM

Description - View 8: Opposite deck edge to show profile of deck cantilever soffit (Picture 015.jpg)

Photo Direction - W

Date of Photo - 10/24/2011 2:00:00 AM

Description - IMG_0024.JPG

Photo Direction - E

Date of Photo - 10/24/2011 2:00:00 AM

Description - IMG_0021.JPG

Photo Direction - W

Date of Photo - 3/22/2006 12:00:00 AM

Description - View 9: Underside of deck (Picture 010.jpg)

Photo Direction - W

Date of Photo - 3/22/2006 12:00:00 AM

Description - View 10: Typical pier (Picture 011.jpg)

FIGURE 2-6: BMS – Inventory Photo Report (Source: SANRAL BMS)

The challenge of monitoring has been expanded by Haardt and Holst (2008) in their assessment of the German BMS. They hold the view that there is a strong need for management solutions during the whole service life of the structure. Structures left unmaintained experience a quicker loss of service life than those that are maintained throughout their life cycle. The typical performance of the respective structures is illustrated in Figures 2-7 and 2-8.

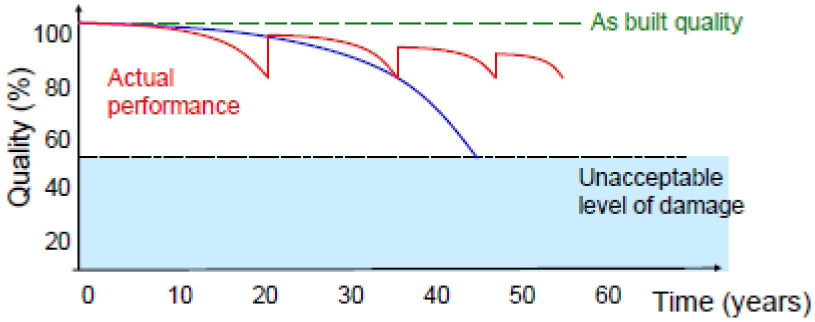


FIGURE 2-7: Service life of concrete structures – Regular maintenance and inspection (Source: Beushausen, 2015).

The structure in Figure 2-7 is the typical deterioration graph of a reinforced concrete (RC) structure that has undergone regular maintenance (approximately every 20 years) and has been subject to intelligent durability techniques through its life cycle. Thus the actual performance of the structure results in a higher standard of quality, which is sustained past its expected design performance. The structure in Figure 2-8 however, also a RC structure, is typical of a structure in a severe environment that has been left unmaintained for long periods and has therefore been left to deteriorate to an unacceptable level of damage. These structures often require expensive maintenance and sophisticated techniques to rehabilitate them.

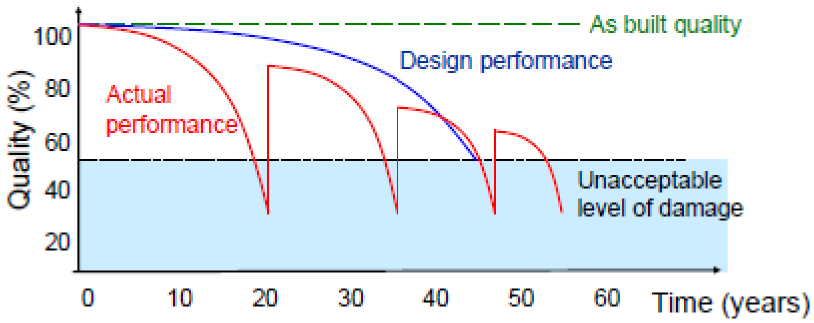


FIGURE 2-8: Service Life of concrete structures – Maintenance irregular (Source: Beushausen, 2015)

Haardt and Holst (2008) describe the German BMS as a basis for advancements to meet future demands. This is because the existing German BMS contains assessment and optimisation procedures on object and network level. They suggest that reasonable infrastructure management will contribute to meeting efficiency and sustainability objectives.

Shaffer and Schellhase (2008) conducted a study on an Integrated Management and Inspection System for Maryland, USA counties and cities. The system is being adopted across the State Maryland and has been designed to provide more efficient and less error prone on-site collection and entry of inspection data. According to the data collected by Shaffer and Schellhase (2008) the counties rely on private consulting firms to perform their inspections. In recent years they have adopted an entirely new process, moving from paper-based data collection to an integrated electronic one, thereby improving the counties' and cities' analysis and accuracy of inspection data. What the system entails is for the consultants to perform an in-depth inspection of the structures and when necessary, to perform new load rating calculations. Basic inventory is stored in a Microsoft Access file and in addition to this an Excel spreadsheet is kept for each task or bridge. This keeps track of soundings, coating conditions and ratings, guard rails, approach data as well as maintenance information. Hejll (2007) expresses the same drawbacks noted by Roux et al. (2010) of visual inspections, that one of the downsides is that defects are only detectable if they reach the surface of the structure, hence the proposed use of SHMS to overcome this challenge. The following section discusses how SHMS have fared in the monitoring of bridges in the past few years.

2.2.2 A review of structural health monitoring systems

Structural Health Monitoring Systems (SHMS) are a non-destructive means of conducting field tests and checking the load-carrying capacity on structures. They are also used in monitoring for the diagnosis of structural damage (Dalton et al., 2013). They aim to give at any moment during the life cycle of the structure a diagnosis of the state of the constituent materials. Balgeas (2006) believes that SHMS are much more than diagnostic tools for non-destructive evaluations. SHMS remove the reliance that is put on expert judgement made from visual inspections and also shifts towards proactive and sustainable infrastructure management.

The condition assessment part of most current bridge management systems is subjective and does not indicate what is going on inside of the structure and requires a person with a lot of experience to understand the structural rating system. Other uses of SHMS include the evaluation of strengthened structures.

A definition of SHMS is given by Heijll (2007) as: A type of system that provides information on demand about any significant change or damage occurring in the structure. Hejll (2007) supports this definition defining SHMS used in the Civil Engineering industry (CSHM) as a method for in-situ monitoring and performance evaluation of civil structures. Hejll (2007) observes the following limitations associated with CSHMS, these include: financial resources, available technology and manpower. These need to be balanced against the objectives that need to be achieved. Another challenge noted is in the understanding of the data output, i.e. what the numbers translate to. The engineers processing and interpreting the data need a strong grasp of the behaviour of structures and the required outcomes from structural health monitoring. The typical components of a Structural Health Monitoring System are shown in Figure 2-9.

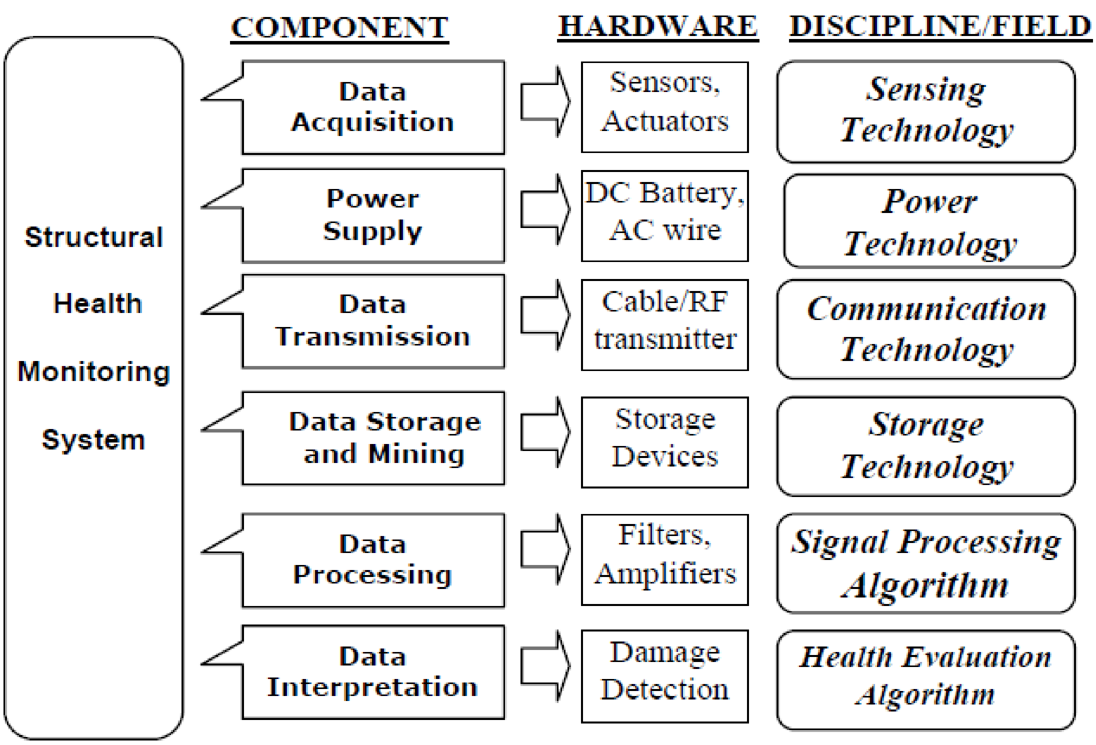


FIGURE 2-9: Typical components of Structural Health Monitoring Systems (Source: Büyüköztürk, 2007)

SHMS comprise sensors, possibly smart materials, data transmission, computational, power and processing abilities within structures (Balgeas, 2006).

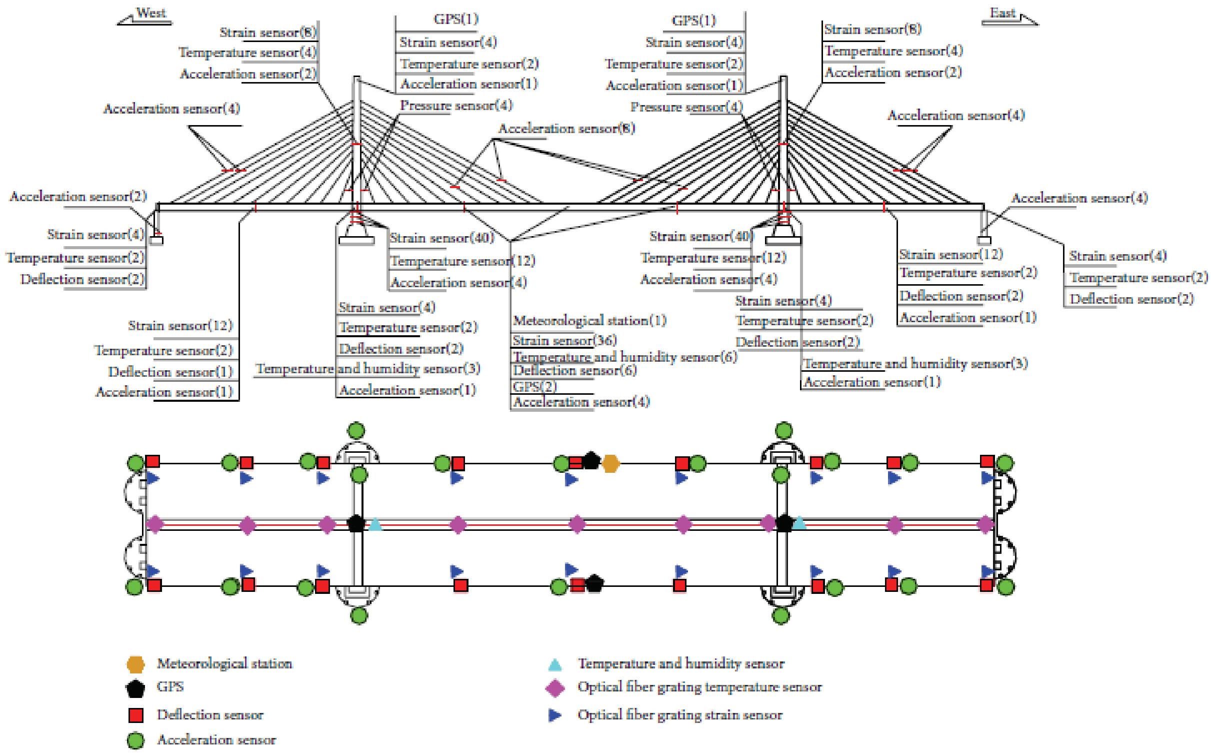


FIGURE 2-10: Layout of sensors on Zhijiang Bridge (Source: Chen, 2014)

They have been used for many years to alert impending failure, impending maintenance as well as damage caused by earthquakes that may not be visible from externally. Figure 2-10 illustrates the organisation of an SHM system as used on the Zhijiang Bridge in China. It demonstrates the use and positions of strain, deflection, temperature and acceleration sensors as well as GPS's and meteorological stations. There are various types of sensors that measure the movements and strain on a bridge. These are: Electrical resistance, fibre optic sensors, vibrating wire sensors and distributed sensors. Various types of monitoring equipment are shown in Figures 2-11 to 2-14:

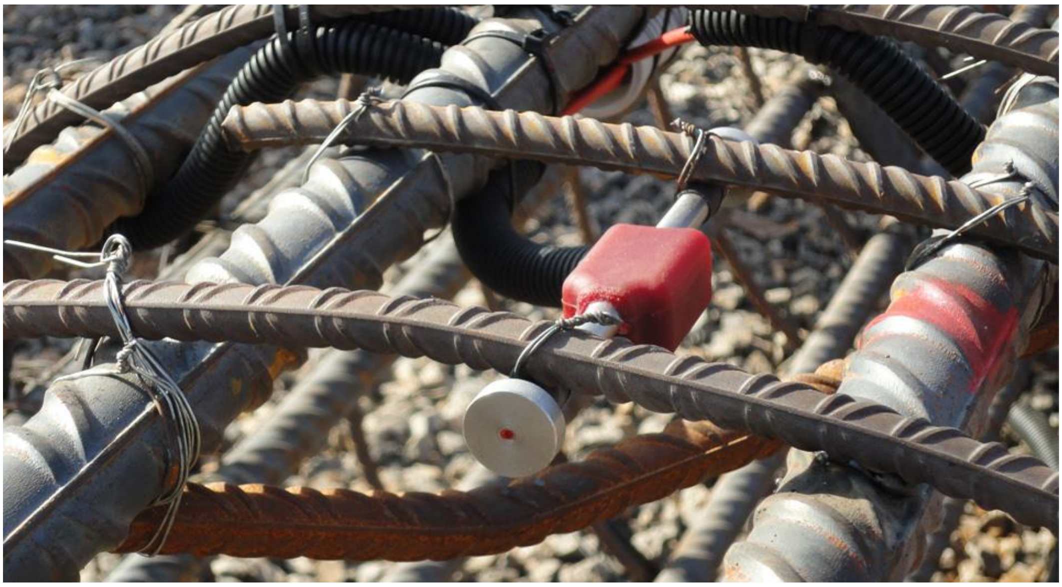


FIGURE 2-11: Casting in of wire sensors into a reinforced concrete structure (http://www.sisgeo.com)

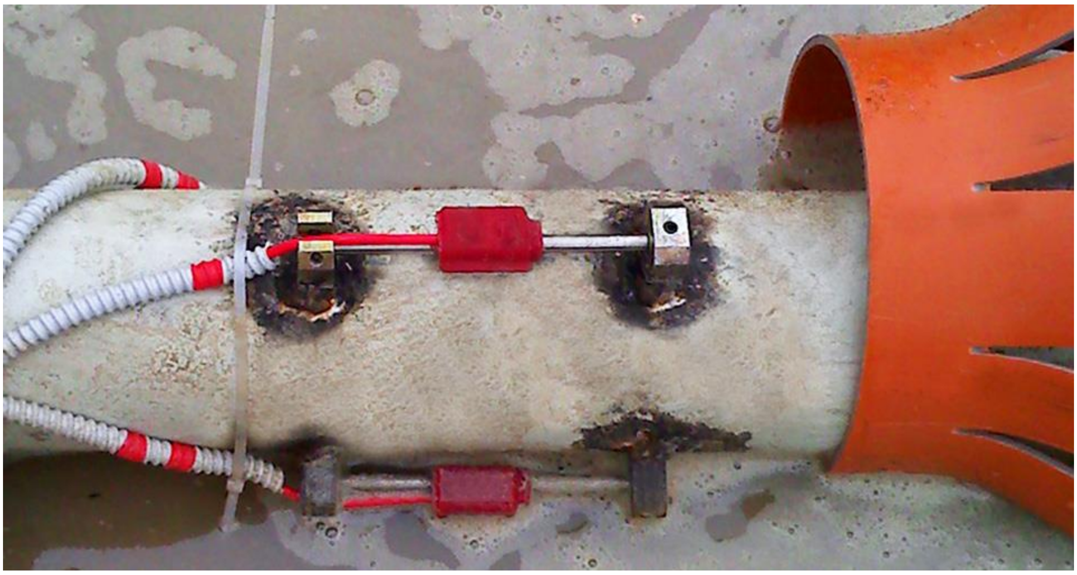


FIGURE 2-12: Vibrating wire strain gauges (http://www.sisgeo.com)

A vibrating wire strain sensor is a non-destructive means of detecting flaws within a structure by using high frequency sound energy to conduct examinations and measurements. The scanners can also be used for dimensional measurements and for characterising materials.

FIGURE 2-13: Ultrasonic Testing (UT) Scanner (Source: Ward, 2016)

An ultrasonic testing scanner is a Non Destructive means of detecting flaws within a structure by using high frequency sound energy to conduct examinations and measurements. The scanners can also be used for dimensional measurements and for characterising materials. Figure 2-14 illustrates a decade of smart sensors. These comprise aspects of radio technology, embedded computing, data storage and local power.

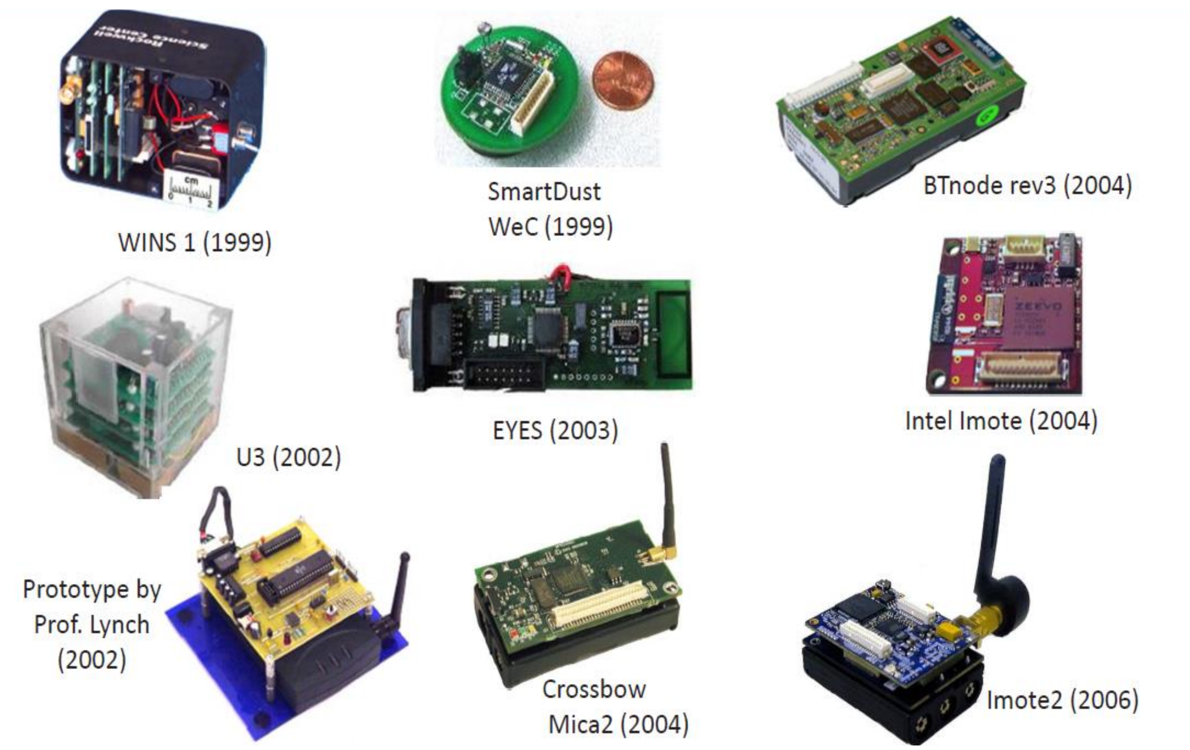


FIGURE 2-14: Historic decade of smart sensors (Source: Spencer, 2013)

According to Van der Wegen at al. (2012), despite many asset owners nowadays requiring a service life on important structures to be 80, 100 or even 200 years, the implicit design life of a typical reinforced concrete structure is 50 years. However, the deterioration of reinforced concrete structures is not always in line with life cycle models. Structures tend to live past the 50-year mark showing very little signs of deterioration, if any. This is because the deterioration of a structure is based on different factors such as: environment, design, construction and materials with which the structure is built as well as fatigue, which reduces the service life of structures.

As part of a management system asset owners conduct routine maintenance, which at times may not necessarily be needed (e.g. repairing an active crack). This is a waste of resources. Conversely, internal degradation for example fatigue induced degradation is often not identified until too late. Transnet Freight Rail (TFR) have increased rail traffic on their heavy haul lines (iron ore and coal) to improve rail efficiencies. This may lead to consequences noted by Busatta and Moyo (2015) such as:

- Larger live load/dead load ratios
- Dynamic amplification
- Reduction of service life due to fatigue

This leads to accelerated deterioration. Busatta and Moyo (2015) conducted dynamic assessments and structural monitoring on a viaduct on TFR's iron ore heavy haul line in order to assist them in making decisions on whether to upgrade, maintain or upscale the line.

The structural health monitoring system on the 45m long bridge consisted of 36 sensors (8 accelerometers, 16 strain transducters, 4 crack sensors and 8 thermocouples) with the aim of monitoring vibration, strain, cracking and temperature. These sensors helped in obtaining valuable information that would assist TFR in making asset 6 decisions (e.g. cracking inside the girder would not have been noted had it not been for the crack monitoring). Busatta and Moyo (2015) recommended the use of a monitoring system to support condition assessment of the viaduct over time and to obtain crucial information for future research work.

The use of SHMS can assist in this regard. Their advantages and disadvantages are discussed:

2.2.3 Advantages of SHMS

- The use of SHMS will replace scheduled and periodic maintenance with performance – based maintenance and thus enable better planning for budgets allocated for the maintenance of infrastructure (Balgeas, 2006).
- The cost of maintenance is also reduced in that the accurate size of a maintenance team would be accurately assessed. SHMS minimise the human error factor thereby improving the safety and reliability of structures.
- Subjective visual assessments of the structure are eliminated.
- The cost of data collection and the logistical challenges of organising tenders for consultants to conduct the work is eliminated.
- The requirement for accuracy in capturing the data is eliminated.
- The data is easier to be analysed as the defects (deflections and other movement) will be known.
- If embedded within the structure, the inventory data of all the structures is already available.
- The logistical challenges are minimised.
- The need for experienced bridge inspectors to conduct visual inspections is removed.
- The use of SHMS will lead to the selection of more appropriate and therefore more cost-effective remedial measure

2.2.4 Disadvantages of SHMS

There are drawbacks associated with SHMS. These include:

- The amount of sensors required per bridge to assess different defects which can get quite costly
- South Africa’s socio-economic conditions may result in the theft of the wires and sensors.
- Continuous and reliable power supply.
- The current cost of the systems may be quite high due to limited availability.
- The complex technical installation of instrumentation may require specialist installers.
- If sensors are embedded within the structure and a fault develops, then the cost of removing or replacing may be high.

Other disadvantages discussed by Zhou and Yi (2013) are low efficiency, susceptibility to disturbance both by humans and nature and their inflexibility where sensor cables have to span from pier to pier. Quick (2011) argues that while newer smart bridges have embedded wire networks of sensors to monitor their structural integrity, the high cost of installing such systems on existing bridges is unaffordable. This has to some extent been overcome by microelectromechanical systems (MEMS). They are low cost and offer on-board computation and wireless communication capabilities. Wireless Network Sensors (WNS) eliminate the need for wires. They offer high efficiency, reliability (as no additional supporting components e.g. long cables, signal analysers and data memory are required) and they offer flexibility because they are organised by wireless transmission.

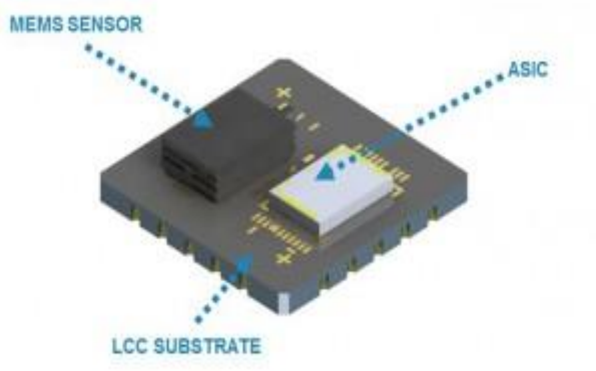


FIGURE 2-15: MEMS accelerometer (Source: www.colibrys.com)

Technologies such as SenSpot sensors that were introduced recently include: micro-structured sensing, ultra-low power wireless communication, and advanced microelectronics which have been compressed into small, and lightweight wireless devices. SenSpot sensors are based on Active RF Test technology (ART), which offers a high performance method for large-scale sensing, wireless synchronization, and ultra-low power wireless communication (Kalantari and Mirbaghen, 2012). These sensors consume less than 4 microwatts of power and provide accurate measurements of strain and tilt. The self-adhesive design aids with easy installation and the software allows a number of bridges to be monitored on one license.

2.3 Bridge Costing

2.3.1 Life Cycle Costing

Whole-life cycle costing (WLCC) also referred to as life cycle costing determines the total cost of a bridge structure from its initial conception to the end of its service life (Ryall, 2010). It has been developed from the initial terotechnology and cost-in-use theories. Life cycle costing (LCC) addresses the shortfalls of cost-in-use theories of the 1970's, which did not enable future forecasting. WLCC encompasses a number of techniques (mathematical, engineering, accounting and statistical methods) to determine net expenditure (Mbanjwa, 2014). Researchers have argued whether WLCC is an improved version of LCC or if the acronyms have been used interchangeably. However, because WLCC takes into consideration aspects beyond LCC, Green (2009) regards WLCC as an evolution of LCC.

WLCC provides the client with a more realistic estimate of how much the bridge structure will cost in the long term (Ryall, 2010). It addresses the problem of the future maintenance of bridge structures and allows designers to project what the impact of their current actions will be in the future. This future projection can be made by conducting a Present Value Analysis (PVA) and working out the Net Present Value (NPV). Life cycle costs assess the cost effectiveness of design decisions, quality of construction or inspection, maintenance and repair strategies (Stewart, 2001). The costs associated in a rehabilitation project may initially include: Initial cost; Maintenance, monitoring, repair cost; Costs associated with traffic delays or reduced travel time (Extra user cost) and failure cost. To estimate the entire Life Cycle Costs, which are the costs associated with the bridge during its whole life, Dhillon (2009) makes use of the following formula:

$$LCC_{br} = CONC + INSC + DESC + FAIC + RAMC \quad \text{..} \quad (2.1)$$

CONC – Construction Cost

INSC – Inspection Cost

DESC – Design Cost

FAIC – Failure Cost

RAMC – Repair and Maintenance Cost

Setunge (2002) gives a formula for maximising the objective function for optimal bridge rehabilitation as:

$$W = B_{lifecycle} - C_{lifecycle} \quad \text{..} \quad (2.2)$$

Where $B_{lifecycle}$ is the benefit that can be gained from the existence of the bridge after rehabilitation and $C_{lifecycle}$ is equivalent to LCC_{br} (the life cycle cost). This benefit does not change regardless of the rehabilitation method considered, thus it is possible to consider only the cost component. Making a decision for the rehabilitation method will be found by minimising the life cycle costs (Setunge, 2002).

Minimise $W = C_{lifecycle}$

a) Net Present Value

Formula 2.3 by (Ryall, 2010) estimates how much an asset is worth in current monetary terms:

$C = P(1 + r)^n$ ………………………………………………………………………….… (2.3)

Where C – Amount in today's monetary terms
P – A principal cost
r – Interest rate
n – Number of years

It can also be expressed in Net Present Value terms *P*, of an expenditure *C* in year *n* at a discount rate *r*:

$P = C/(1 + r)^n$……………………………………………………………………….….. (2.4)

The above formula does not take into account the other expenses associated with a bridge such as abutments, piers, deck, bearings, expansion joints, etc. thus this cumulative present value is (Ryall, 2010):

$\Sigma P = \Sigma C/(1 + r)^n$……………………………………………………….………… (2.5)

The process of calculating NPV is known as discounting and the terms interest rate and discount rate are interchangeable (Ryall, 2010).

2.3.2 Replacement Costs

i) Depreciation Cost (National Treasury, 2012):

Depreciation allocates the original cost of an asset to an expense in the periods in which the asset is consumed. Depreciation is calculated whether the asset is in use or idle. Accumulated depreciation is the portion of an asset's original cost that has already been written off as a depreciation expense in prior periods. The depreciation charge for each period is recognised as an expense.

- Depreciated Replacement Cost (DRC) is a measure of the current value of an asset based on its current replacement cost less an allowance for deterioration of condition to date.

- DRC is an accepted fair value calculation for assets where there is no active and liquid market.
- It has also become an integral part of the infrastructure management approach.
- Depreciated replacement calculation is summarised in the formula 2.6:

DRC = CRC x RUL / EUL………………………………………………………………….… (2.6)

Where:

- CRC = Current Replacement Cost.

The cost of replacing an existing asset with a modern asset of equivalent capacity.

- RUL = Remaining Useful Life

When an assets life reaches zero, it needs to be replaced.

- EUL = Estimated Useful Life

The period over which an asset is expected to be available for use by an entity, it assumes a particular level of planned maintenance.

The National Treasury (2003) gives the Estimated Useful Life for bridges and culverts in Table 3:

TABLE 3: Estimated Useful Life for bridges and culverts (Source: National Treasury, 2003)

Type of structure	Material	Estimated Useful Life (Years)	
		Minimum	Maximum
Bridge	Concrete	60	80
Bridge	Steel	40	50
Bridge	Timber	25	40
Expansion and construction joints		15	20
Culvert	Concrete	40	60
Culvert	Corrugated Iron	25	40
Retaining Walls	Reinforced Concrete	25	30

The costs associated with bridges vary depending on the bridge system used. The selection of the most cost effective bridge system is usually determined by the total length and width of the bridge. For a simplistic approach in determining the costs, a total length range is given a cost/m^2 rate (Shown in Table 5). There are other factors that need to be taken into account with this rate which will require the unit rate to be adjusted. The unit rate must be adjusted for (National Treasury, 2012):

a) P&G Items, including
   - Accommodation of traffic
   - Environmental management

b) Planning, Design and Overhead Costs
   - Road Authority Planning Costs (+5%)
   - Design, Supervision and Tech Services Cost (+15%)
   - Road Authority Administration Costs (+10%)
   - Total Adjustment (exclusive of VAT) (+30%)

The unit rate in Table 5 should also take into account the topography, the soil conditions and foundation type that is selected, as these can have a significant effect on the construction costs. Table 4 is given in the event that the bridges are replaced with a similar type bridge. It offers CRC unit rates per m^2 for various bridge types.

TABLE 4: Current Replacement Cost Unit Rates (Source: TMH 22, 2013)

Component Type	Category	Unit	CRC Rate (Rand 2013)	EUL
Bridge - General	Max. pier/abutment height < 8m	m^2	20 800	80
Bridge – General	Max. pier/abutment height 8 to 30m	m^2	CRC = 946*H + 13 235 where H = maximum pier/abutment height in m	80
Bridge – General	Max. pier/abutment height > 30m	m^2	41 600	80
Bridge – Arch	Max span length < 100m	m^2	41 600	80
Bridge – Arch	Max span length 100 to 200m	m^2	CRC = 208*L + 20 800 where L = maximum span length in m	80
Bridge – Arch	Max span length > 200m	m^2	62 400	80
Bridge - Cable	Max span length < 150m	m^2	52 000	80
Bridge - Cable	Max span length 150 to 300m	m^2	CRC = 277*L + 10 400 where L = maximum span length in m	80
Bridge - Cable	Max span length > 300m	m^2	93 600	80
Bridge – Cellular	Fill above bridge 0 to 3m	m^2	16 900	80
Bridge – Cellular	Fill above bridge 3 to 6m	m^2	20 280	80
Bridge – Cellular	Fill above bridge 6 to 10m	m^2	23 660	80
Bridge – Cellular	Fill above bridge > 10m	m^2	27 040	80

Many infrastructure asset managers nowadays have limited funds for asset maintenance, rehabilitation and replacement, thus the probability of a bridge system being replaced by one similar is unlikely to happen. A guideline by 3 bridge design consultants in South Africa, on the most economical system for the various span ranges and the cost/m^2 is given in Table 5.

TABLE 5: The most cost effective bridge system per span.

Span Length	Bridge System	Cost/m^2
6 – 15m	Solid Deck	R 15000.00
15 – 30m	Pre Cast Beams	R 20 000.00
30 – 500m	Box girder (Incrementally launched)	R 25 000.00
	Box girder (Cast in-situ)	R 30 000.00

ii) Impairment Methods (National Treasury, 2012):

- Impairment is a loss in the future economic benefits or service potential of an asset, <u>over and above depreciation.</u>
- Impairment means the carrying amount of an asset exceeds its recoverable amount or recoverable service amount.
- If an asset is impaired, it should be written down to its recoverable amount.

2.3.3 Bridge Inspection Costs

The STRUMAN BMS requires accredited bridge and culvert inspectors to conduct inspections. Table 6 shows the costs of a contract for SANRAL bridge inspections that were conducted in 2016. With the added yearly escalation costs, the average bridge inspections in 2017 are for the purposes of this research estimated at a cost of R 6500.00 per bridge and culvert inspections at R 4500.00 per culvert.

TABLE 6: SANRAL bridge inspection costs 2016.

SANRAL CONTRACT SCHEDULE OF QUANTITIES

Schedule A: Northern Region (NR) Structures

Group	Item	Item Description	Unit	Qty.	Unit Rate	Total
NR02	1	Establishment and de-establishment of personnel and equipment on site	Lump Sum	1	R 60 874.79	R 60 874.79
	2	Equivalent bridge Units	no	120	R 5 595.88	R 5 595.88
	3	Major Culverts	no	24	R 3 848.24	R 3 848.24
Verification No. 45822C8F31FA71E0F89587A3A88E173E					Total	R 824 738.15

Group	Item	Item Description	Unit	Qty.	Unit Rate	Total
NR02	1	Establishment and de-establishment of personnel and equipment on site	Lump Sum	1	R 63 155.19	R 63 155.19
	2	Equivalent bridge Units	no	68	R 5 595.88	R 380 519.84
	3	Major Culverts	no	17	R 3 848.24	R 65 420.08
Verification No. 45822C8F31FA71E0F89587A3A88E173E					Total	R 509 095.11

2.3.4 Importance of bridges

Generally, problems with the lack of maintenance of facilities and poor service quality, shift the burden of infrastructure provision and often increase the overall costs. This results in outcomes that are not the most economically efficient. Investments in infrastructure yield economic benefits only to the extent that they generate a sustainable flow of services valued by the customer.

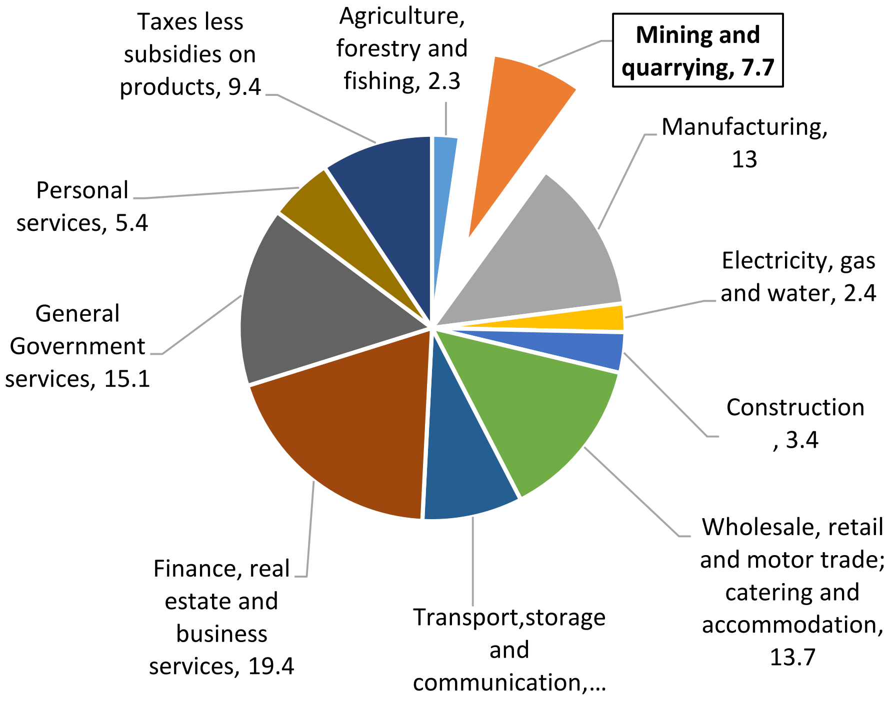
Kessides (1993) suggests that to gain more insight into how infrastructure contributes to economic growth and improved quality of life, it is necessary to consider microeconomic evidence. Microeconomics shows how and why different goods have different values and how individuals make more efficient or more productive decisions.

Drawing from the above statement and linking it with the case study of the Ermelo to Richards Bay coal line, it can be deduced that the cost of not maintaining the bridges on this coal line will negatively affect the output of the transportation of coal. In order to make that conclusion it needs to be established what contribution coal makes to the South African economy.

There are three named sectors of an economy: The primary, secondary and tertiary sectors. The early phases of an economy are usually dominated by primary sector activities such as agriculture and mining. The secondary sector economy is brought about by the establishment of the primary sector and is characterised by manufacturing, shopping centres, police stations, medical services, water, electricity, etc. and the tertiary sector is characterised by professional services such as financial and governmental (Mohr, et al., 2008).

With the growth of South Africa's secondary and tertiary sectors, the relative contribution of mining to South Africa's Gross Domestic Product (GDP) has declined over the past 10 to 20 years. However, mining still accounts for 50% of the volume of TFR's rail and ports (TFR, 2015). South Africa plays an important global role in the export of minerals and produces a large variety of minerals. Exports are dominated by gold, coal, diamonds and platinum group metals. Coal is the most abundant of fossil fuels and accounts for 40% of the world's electricity, which the World Energy Council estimate at being set to continue for three decades.

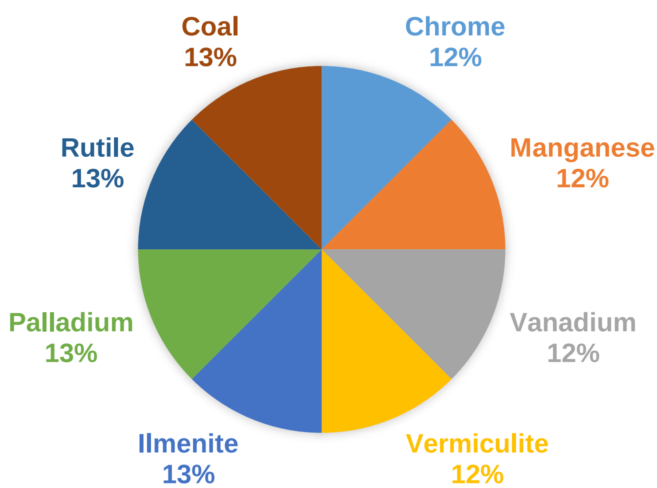
Tripathi et al. (2016) suggest that, with major and minor reserves of minerals such as diamonds, gold, iron and coal (among others), minerals are the main driving force behind South Africa's economy. This makes mining and quarrying (in 2013) the 6th largest contributor to the annual economic growth rate, Figure 2-16. The percentage division of South Africa's mineral exports is shown in Figure 2-17. The country is the world's largest producer of chrome, manganese, platinum, vanadium and vermiculite and the 7th largest producer of coal. South Africa produced 142.9 Mt in 2015 (Dudley, 2016) and is the 6th largest exporter, exporting 74 Mt in the same year.



Minerals and quarrying contributed 7.7% to South Africa’s GDP in 2013. (GDP in 2013 was 367.59 billion US dollars) This means the sector contributed $28.3 billion US.

Relative size 2013 (per cent)

FIGURE 2-16: Contribution of the percentage change in real value added by industry to the total real annual economic growth rate - real GDP at market prices (Source: Statistics South Africa, 2014)



Minerals contributed 20.6% to South African Exports in 2015.

FIGURE 2-17: South Africa’s mineral exports for 2015 (Dudley, 2016)

Despite South Africa experiencing a large growth in the services sector, Mohr, et al (2008) highlight that the South African economy is still heavily dependent on the exploitation of its mineral resources. With coal reserves estimated at 30 156 Mt (at the end of 2015) by the World Energy Council, the country still holds about 3.4% of the world's reserves of coal (see Table 7). Coal is thus still a major income generator for the country. Coal is used in many applications, most prominently in electricity generation, steel production and cement manufacturing and as a liquid fuel. Not maintaining the supporting infrastructure would cripple the ability of South Africa to engage in international trade, even of the traditional export of commodities. A fight for new global export markets is even more dependent on infrastructure (Kessides, 1993).

TABLE 7: Total proved coal reserves at end 2015 (Source: Dudley, 2016)

Coal

Total proved reserves at end 2015

Million tonnes	Anthracite and bituminous	Sub-bituminous and lignite	**Total**	Share of total	R/P ratio
US	108501	128794	**237295**	26.6%	292
Canada	3474	3108	**6582**	0.7%	108
Mexico	860	351	**1211**	0.1%	84
Total North America	112835	132253	**245088**	27.5%	276
Brazil	–	6630	**6630**	0.7%	*
Colombia	6746	–	**6746**	0.8%	79
Venezuela	479	–	**479**	0.1%	*
Other S. & Cent. America	57	729	**786**	0.1%	244
Total S. & Cent. America	7282	7359	**14641**	1.6%	150
Bulgaria	2	2364	**2366**	0.3%	66
Czech Republic	181	871	**1052**	0.1%	23
Germany	48	40500	**40548**	4.5%	220
Greece	–	3020	**3020**	0.3%	63
Hungary	13	1647	**1660**	0.2%	180
Kazakhstan	21500	12100	**33600**	3.8%	316
Poland	4178	1287	**5465**	0.6%	40
Romania	10	281	**291**	♦	11
Russian Federation	49088	107922	**157010**	17.6%	422
Serbia	1	13410	**13411**	1.5%	352
Spain	200	330	**530**	0.1%	173
Turkey	322	8380	**8702**	1.0%	192
Ukraine	15351	18522	**33873**	3.8%	*
United Kingdom	228	–	**228**	♦	27
Uzbekistan	47	1853	**1900**	0.2%	481
Other Europe & Eurasia	1388	5494	**6882**	0.8%	187
Total Europe & Eurasia	92557	217981	**310538**	34.8%	273
South Africa	30156	–	**30156**	3.4%	120
Zimbabwe	502	–	**502**	0.1%	121
Other Africa	942	214	**1156**	0.1%	122
Middle East	1122	–	**1122**	0.1%	*
Total Middle East & Africa	32722	214	**32936**	3.7%	123
Australia	37100	39300	**76400**	8.6%	158
China	62200	52300	**114500**	12.8%	31
India	56100	4500	**60600**	6.8%	89
Indonesia	–	28017	**28017**	3.1%	71
Japan	337	10	**347**	♦	296
Mongolia	1170	1350	**2520**	0.3%	103
New Zealand	33	538	**571**	0.1%	168
Pakistan	–	2070	**2070**	0.2%	*
South Korea	–	126	**126**	♦	71
Thailand	–	1239	**1239**	0.1%	82
Vietnam	150	–	**150**	♦	4
Other Asia Pacific	713	1075	**1788**	0.2%	37
Total Asia Pacific	157803	130525	**288328**	32.3%	53
Total World	**403199**	**488332**	**891531**	**100.0%**	**114**
of which: OECD	155494	229321	**384815**	43.2%	206
Non-OECD	247705	259011	**506716**	56.8%	85
European Union	4883	51199	**56082**	6.3%	112
CIS	86524	141309	**227833**	25.6%	435

A non-renewable resource such as coal will be exhausted in the future (Dudley, 2016), therefore the exploitation of coal exports still plays a very important role in the economy of South Africa.

2.4 South Africa's infrastructure challenge

South Africa as a country with competing interests for various infrastructure requirements, will face increasing challenges in supporting the country's needs while trying to remain globally competitive. In addition to this, shown in Figure 2-18, the country has drastically reduced public sector investment (per share of GDP) while the private sector has remained consistent over the past few decades. According to Chapter 5 of the 20-year National infrastructure plan, public sector infrastructure delivery involves many different implementing spheres of government – national, provincial and local, as well as their agencies and entities, including the large state-owned enterprises such as Eskom and Transnet, which are key players in many sectors.

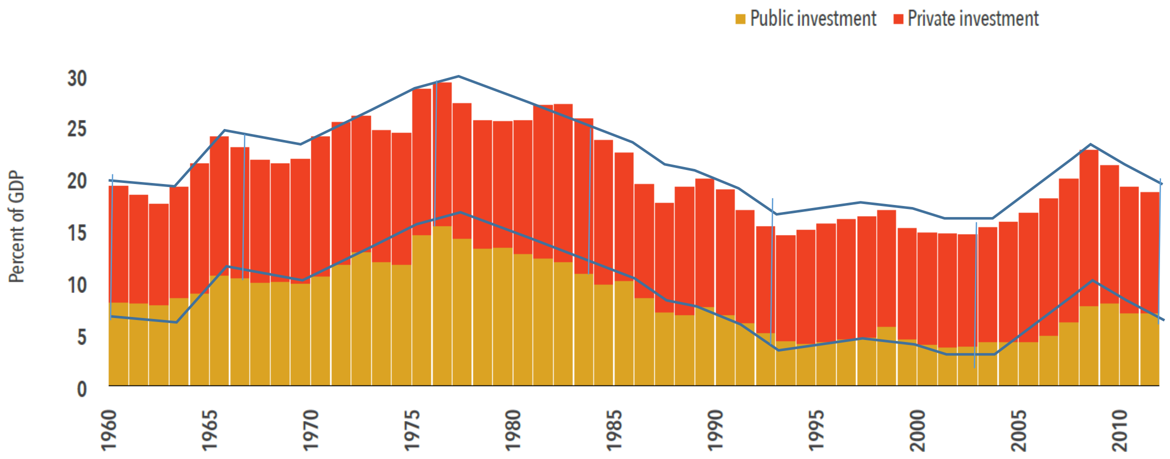


FIGURE 2-18: Public and private-sector capital investment as a share of GDP, 1960-2010 (Source: South African Reserve Bank, as cited in 2012 budget review)

The decline in public investment in infrastructure leads to a decline in maintenance investment. This is happening increasingly and when investments are low, maintenance is deferred. Boshoff et al. (2013) highlight this in the 2013 State of cities' finances report.

This report documents an increase from 25% to 30% in bulk purchases and notes the pressure it has placed on general expenses, repairs and maintenance, thus repairs and maintenance as a percentage of total expenditure decreased from 7% in 2009 to 6% in 2011. The remaining spend on infrastructure has been directed to stadiums, harbours, rail, airports and national roads. Wall (2011) argues for maintenance, highlighting that the longer maintenance is delayed, the higher the cost of repair work and also that infrastructure may have to be replaced well before the end of its intended life.

In addition to the decline in public investment, the country battles with a prioritisation of infrastructure. Boshoff et al. (2013) argue that on the one hand there is a need to roll out new infrastructure to poor and excluded communities, while on the other, there are infrastructure assets that represent the current tax base and need to be maintained and expanded. In an effort to redress the country's apartheid legacy there is a backlog in housing, water and sanitation infrastructure. This type of infrastructure, i.e. social infrastructure does not yield an immediate return on investment, but is nonetheless necessary. As the migration to large cities for better economic opportunities increases, the strain on the current infrastructure is exacerbated. However, in an effort to remain globally competitive, the country needs to maintain current economic infrastructure and increase the capacity of ports, rail and airport infrastructure.

The South African Institution of Civil Engineering (SAICE) gave South Africa's infrastructure an overall score of D in the 2006 infrastructure report card (SAICE, 2011). The 2011 SAICE report card indicates an improvement to the national infrastructure of ports, rail, airports and national roads since 2006. Rail infrastructure for heavy haul freight lines scoring a B+ indicates "a relatively good condition, proper maintenance, with a capability of dealing with minor incidents" (SAICE, 2011). This necessitates that these 'minor incidents' or operational issues are resolved in order to maintain this rating.

The data from the case study in Chapter 5 indicates that 20% of the bridges on the line under study were constructed between 1965 and 1969. The bulk of the bridges (42.7%) were constructed between 1970 and 1974.

This indicates that nearly two-thirds of the TFR bridges on the coal line from Ermelo to Richards Bay are either approaching or are half way past their 100-year design life. At this stage, as illustrated in Figure 2-8, the assets are assumed to have reached an unacceptable level of damage and any attempts at restoration would do little to restore the asset to the expected quality levels. However, as previously noted, this model is a theoretical model and structures may not have necessarily reached this unacceptable level of damage. Therefore, the costs of restoration and renewal of the asset would need to be evaluated to decide on how best to deal with the actual remaining useful life of the asset.

2.5 Conclusion

Bridges connect people to economies. When well designed, bridges form a resilient means of transporting goods and connecting people over geographical features. BMS has been around for many years and has been an effective tool for monitoring the health of bridge structures. However, the shortcomings of BMS and the ageing of a large portion of the world's infrastructure has promoted research into technologies such as SHMS.

SHMS have revolutionised the way that bridge monitoring is regarded. It offers more accurate information of the condition of structures. However, it too has its own challenges, some of which are continuously being addressed by improvements into this technology. It seems that there is a conjuncture, particularly in the developing world where the implementation is low to non-existent. Continents such as North America, Europe and Asia are already using SHMS as a means of preventative maintenance.

In countries with a prevalence of snow (and the use of de-icing salts, which accelerate corrosion) and harsh climatic conditions with extreme temperature variations, SHMS are able to alert asset managers of impending maintenance. Developing countries like South Africa do not experience extreme temperature variances in most parts of the country, but do have a serious backlog in maintenance. With increasing usage of bridge assets and a pressure on budgets, Chapter 3 assesses whether there is a case to be made for the implementation of SHMS on South African bridges and whether the ideal time to do so is now.

CHAPTER 3

3 ECONOMIC VALUE OF STRUCTURAL HEALTH MONITORING SYSTEMS

3.1 Introduction and Problem definition

The services sector has enabled South Africa to become globally competitive. In order for that to be maintained, a large investment has to be made in the infrastructure sector. Investors want to do business in countries that have infrastructure in a good working condition. Low investments into a country can influence growth prospects of the country's economy. A decline in economic growth can lead to a decline in employment affecting a large percentage of the South African workforce. Therein lies value and a responsibility for the country to maintain its infrastructure.

The economic value of goods or services is defined as a function of preferences of a given population (sample) and the trade-offs its members make given their resources. In other words, a measure of benefit provided by a good or service. Economic value is also directly correlated to the value that any given market places on an item. The definition is further expanded to suit different sectors of the economy: consumer goods, marketing and other sectors. This perception of economic value changes in the case of consumer goods and is not seen as a static figure, but rather malleable to changes when the price or quality of similar items change.

If this definition is extended to bridge structures, it can be seen to mean that the value of a country's bridges is only as valuable as the level to which they provide the users with benefit. The relationship between SHMS and providing this benefit is directly proportional. In order to determine what level of benefit they provide, SHMS are compared to their current BMS counterparts and the following three statements are explored:

i) The benefit obtained from the bridge serving its purpose.
ii) The value of the bridge at any given time throughout its life cycle.
iii) The current BMS versus using SHMS for monitoring.

3.1.1 Cost benefit for purpose

It was determined in the introduction that the importance of bridges lie in the purpose that they serve. It can be assumed that the value placed on the importance of railway lines such as the Ermelo-Richards Bay line (used in the case study) as a transport means for coal, will be dependent on how long the line is expected to transport coal as well as the demand that is there for coal exports from South Africa. For example, it can be correlated that the reduced demand for coal in China and the subsequent drop in the value of coal exports reduced the value of the line. The global deceleration in global energy consumption was caused by a slowing down of China's industrialisation.

The cost of maintaining bridges on the coal line may impact on revenue and the cost may be recovered from increasing the transportation costs of coal (and other commodities transported on the line). Increased transportation costs in turn results in increased coal prices. The law of supply and demand is such that when the price of coal transported on the Ermelo-Richards Bay line increases, the demand for this coal is reduced. Therefore, the cost-effectiveness of the bridge management programme may ultimately affect coal exports from South Africa.

In order to make resource allocation decisions based on economic values, the net economic benefit from goods needs to be measured. The economic benefit to individuals (consumer surplus), received from goods will change if its price or quality changes. Perhaps one of the reasons why SHMS have not been popular in South Africa despite being available for many years worldwide is because the economic benefit has not been fully appreciated by bridge infrastructure asset owners. Alternatively, it could be that the cost trade-off is too high when compared with current management systems. It could also be that some existing techniques for structural health monitoring suffer from non-scalability due to the high cost of instrumentation devices, large installation costs (e.g. due to wiring needs), or high maintenance costs (Kalantari and Mirbaghen, 2012). Another reason could be that they are not readily available on the market which according to Figure 3-1, will make them costly - Unit costs decline as the volume of output increases (Kessides, 1993).

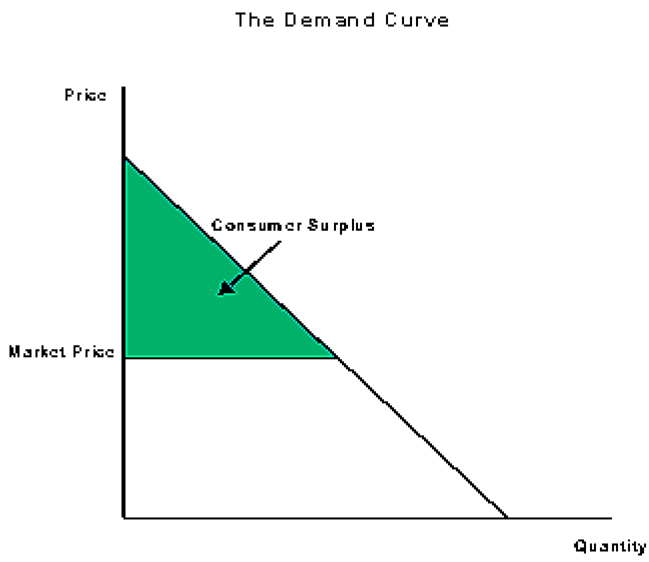


FIGURE 3-1: The demand curve (Source: ecosystemvaluation.org)

Furthermore, the performance of concrete bridges in South Africa may not warrant the use of SHMS. Bridges in South Africa generally perform well. However, many of the bridges on the coal line were constructed over 50 years ago and thus will be approaching their EUL. The fact that bridges reach their EUL is not necessarily an issue, as bridges can continue to function past their EUL. The issue lies in the fact that most of the bridges will reach their EUL at the same time. With the gradual decline of public investment in infrastructure since 1976 (shown in Figure 2-18), denoting a smaller pool of budgets, asset owners are having to do more with less.

The initial costs attributed to SHMS are high as they consist of capital costs and installation costs. Over time the costs are reduced as they consist of data processing and operating costs. In contrast, while the inspection costs of BMS start off low, the frequency and inflation of inspection costs over time can result in them being quite high. The point in time where the most benefit is obtained from both SHMS and BMS, derived in Figure 3-2, is where the most economic value is found.

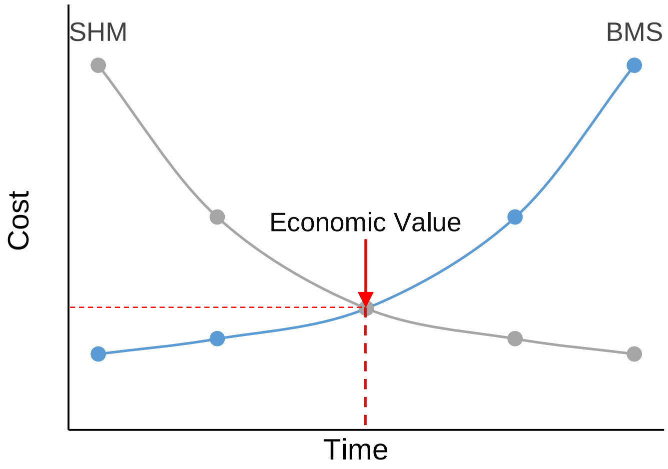


FIGURE 3-2: The relationship between SHMS and BMS over time.

3.1.2 The value of the bridge at any given time throughout its life cycle.

The activities involved in life cycle asset management are shown in Figure 3-3. The role of an asset manager involves analysing future levels of service and the gap between the current capability of the asset and its ability to meet its future demands. This model is not only applicable to municipal asset managers, but can also be applied to asset managers such as Transnet Freight Rail who are reliant on the effective operation of their infrastructure assets in order to meet their clients' demands (e.g. increased demand for coal).

Life cycle asset management starts with the creation or acquisition of an asset, then operations, condition or performance assessment, maintenance and/or the upgrade of the asset, asset renewal or disposal of the asset and finally, assessing the future demand service of the asset in order to determine what to do with it. For maintenance to be instituted a condition assessment is required which informs the decision on whether the assets should be upgraded, renewed or disposed of. This decision is influenced by assessing the future demand or the service required from the asset.

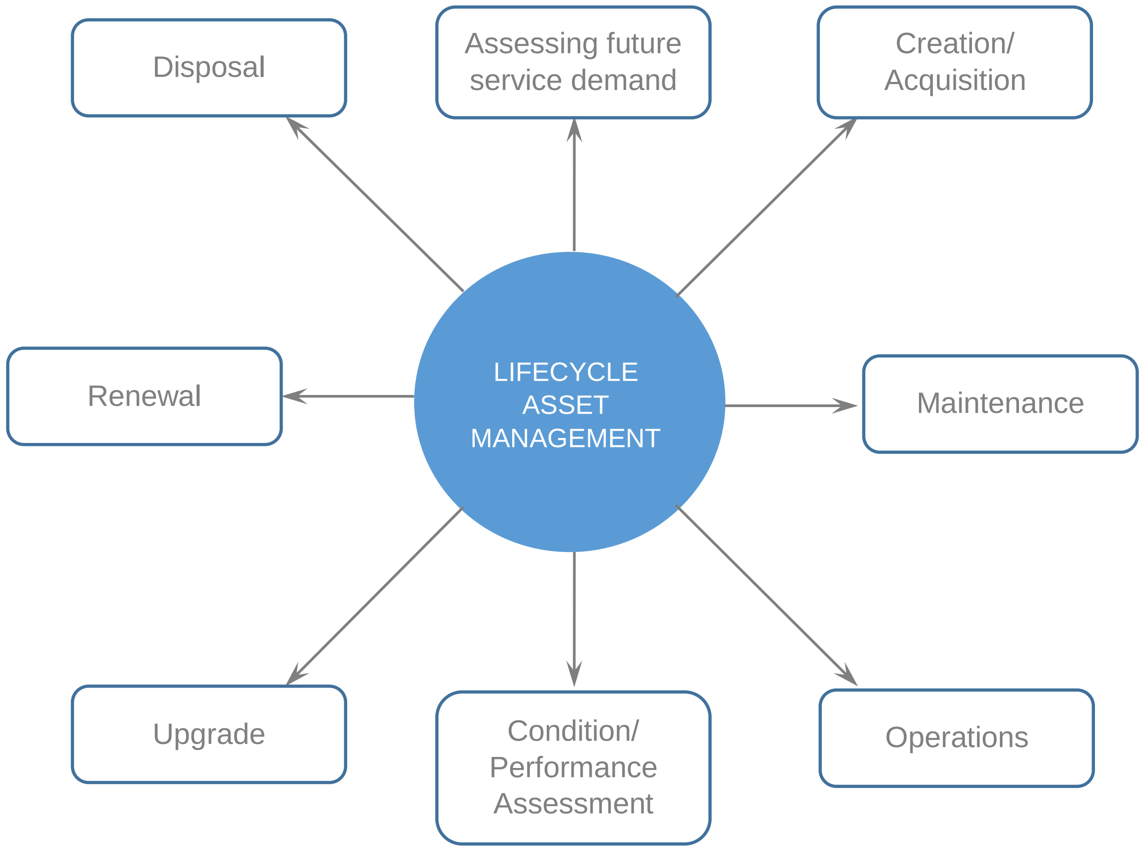


FIGURE 3-3: Lifecycle Asset Management - Network of infrastructure assets. (Source: IMESA, 2011)

The acts of creating/acquiring and disposing of an asset (at the end of the asset's life), remain constant. There are certain activities required for the lifecycle of an asset to be fulfilled which can be circumvented using SHMS. Not only do SHMS allow for optimal decision-making, but they also allow for *accurate* optimal decision-making. SHMS monitor the condition throughout the life of the structure, alert asset managers on whether to upgrade, renew or dispose of the asset, as well as the timing thereof. With information provided by SHMS on the internal condition of the structure, asset managers know best how to optimise operations and when to conduct maintenance, upgrade or renewal.

If asset managers such as TFR are responsible for a large number of bridges, SHMS allow them to prioritise which bridges to conduct maintenance on first. If the actual defects on the bridges are known, it makes it easier to determine the type of maintenance needs that are required by the bridges. The use of SHMS to eliminate steps in the asset life cycle (shown in Figure 3-3), is illustrated in Figure 3-4.

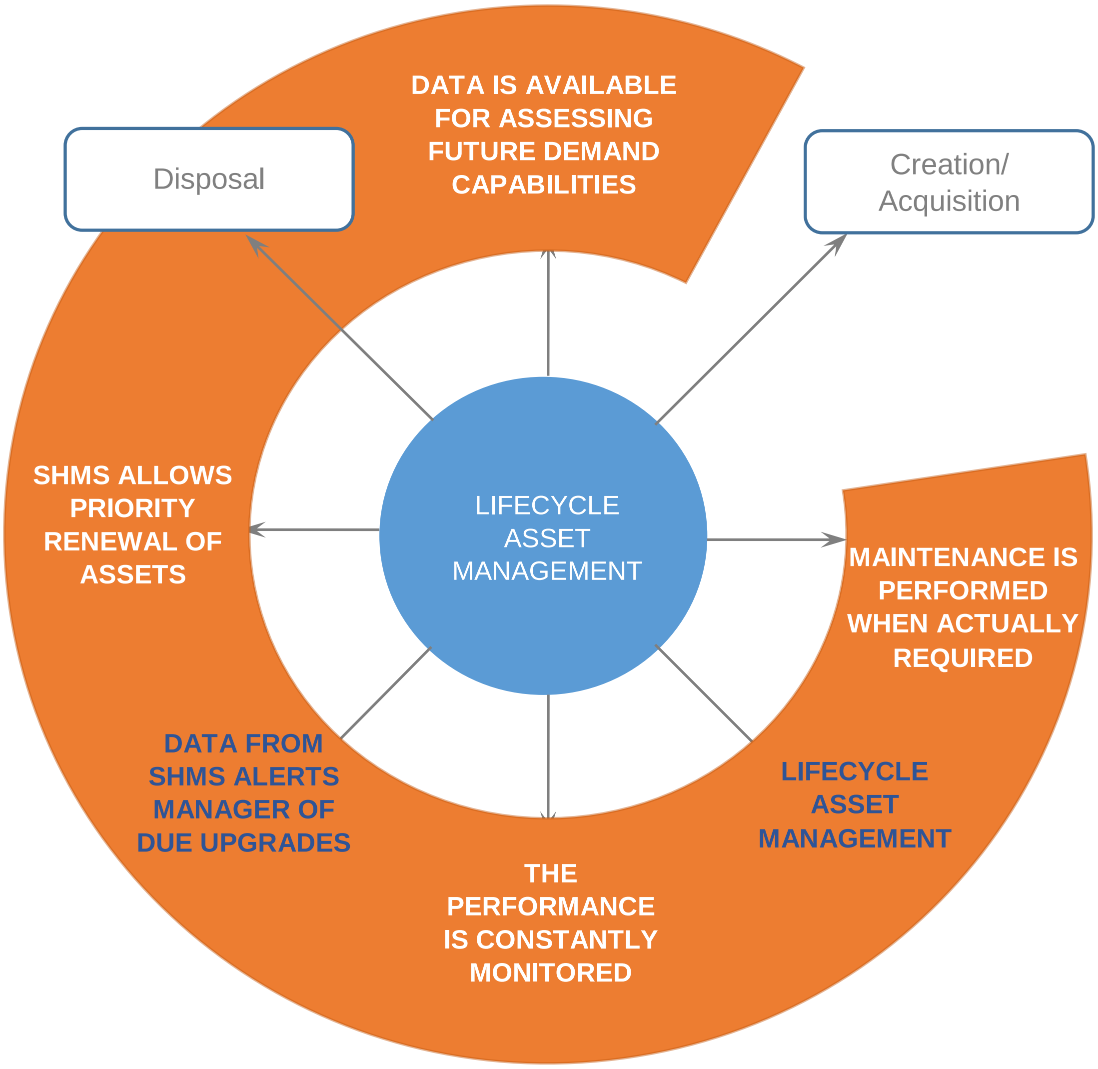


FIGURE 3-4: Lifecycle Asset Management - Network of infrastructure assets using Structural Health Monitoring Systems

3.1.3 The current BMS versus using SHMS for monitoring.

Bridge performance can be expressed in terms of reliability. In the bridge assessment procedure, the reliability of the bridge can be compared against an acceptable limit of the reliability (Setunge, 2002). Where the uncertainty of budgets and safety concerns exist, reliability is questioned. This warrants research into alternative methods such as SHMS for keeping structures safe, but also questions the value of applying SHMS as an alternative for the current methods of condition assessment on bridges.

Both BMS and SHMS have costs associated with them. A distinction needs to be made between the use of SHMS for structural monitoring and SHMS for in-situ structural inspection. The distinction is best explained by Derriso et al. (2014) who base it on three primary factors: the rate of evaluations, the use of previous evaluation outcomes and the range of possible decisions provided by the evaluation process. Derriso et al. (2014) describe inspections as evaluations that provide a pass/fail assessment of the integrity of a component whereas monitoring is defined as a process that tracks the integrity of a component across time using a sequence of evaluations taken often to allow a wide range of possible decisions regarding the future operation of the component.

SHMS for monitoring and for in-situ inspections are compared with the list of costs expected with a BMS in Table 8:

TABLE 8: Cost items associated with monitoring systems.

BMS	SHMS on a built structure	SHMS in-situ
Procurement	Bridge Engineer and Team	Procurement, site personnel and installation included in project cost
Bridge Engineer and team	Analysis of existing structure	-
Inventory data collection	Inventory data collection	-
Visual Inspections	Visual Inspections	-
Detailed Inspections	System installation	-
Data Analysis	Data Analysis	Analysis of data for maintenance

Table 8 indicates that the activities required for BMS and SHMS are only truly differentiated when SHMS are used for in-situ inspections. The costs may be skewed in favour of SHMS based on the once off capital cost (when used for in-situ inspections).

Economic value is one of the many possible ways to define and measure value. With economic values, choices can be made that involve trade-offs in allocating resources. The measures of economic value are based on preferences, in this case BMS or SHMS and the trade-offs involved with both systems. In the South African market economy, the Rand currency will be used to measure economic value. It entails looking at the trade-offs, given certain constraints, that can be made in order to purchase a good or service.

3.2 Conclusion

Inaudi (2011) discusses the hard and soft benefits for the implementation of SHMS. Hard benefits are those that can be economically quantified, such as immediate / deferred cost savings or increased value. Soft benefits are the intangible benefits that the owner of a SHM system perceives and for which he/she is willing to pay a price. Soft benefits cannot directly be quantified. Inaudi (2011) also believes that there is a benefit which is a combination of the two, for example a reduction of risk could lead to a savings in insurance costs and an increase in safety, thereby creating both a hard benefit (a decrease of costs) and a soft benefit in terms of peace of mind.

Due to a lack of information on the number and causes of bridge collapses in South Africa, data from the USA will be used to establish the underlying cause of collapses. This type of data varies from country to country. Most bridge failures (failure defined as the inability of a bridge or one of its primary load-carrying components to no longer perform its intended function) in the USA, occur during the service life of the structure. In an analysis of the causes of bridge failures from 1989-2000, Wardhana and Hadipriono (2003) attributed the most frequent failures to be caused by flooding and collisions.

If these two causes were taken as the determinate causes of failure, a bridge management system that relies on routine inspections will not be useful in the case of a flood, unless there is irreparable damage to the structure, in which case a new structure would need to be constructed. In the case of a collision, unless there are visible signs of damage, the true extent of the damage cannot not be ascertained. The reliability rests on the visual inspection, but does not give an indication on what damage has actually occurred within the structure, if any. Further tests may be required in the case of BMS, by taking cores and assessing visible and micro cracking. With SHMS, information pertaining to strain as a result of collision is sent through to a computer system and the position of the damage can be located.

TFR realises the need to run a 24-hour operation in order to meet global export demands. The case study in Chapter 5 analyses the current operations of TFR. It helps to unpack whether their current bridge management system is the most ideal means of monitoring their bridges or whether there is economic value in the installation of Structural Health Monitoring Systems. The methodology is discussed in Chapter 4.

Other activities that are required with SHMS are such that current BMS cannot completely be eliminated. Decisions on funds to be allocated to particular infrastructure, when to dispose of the asset and how to prioritise structures, still need human intervention. The costs involved with current BMS need to be compared with the costs of SHMS. The value though, is obtained by considering the short and long term benefits. A comparison should also be made to determine whether there is more benefit in autonomous in-situ (embedded within the structure) devices versus installing SHMS at a later stage. Advancements have been made and are discussed by Lallart et al. (2010) in the future of autonomous devices for in situ health monitoring. This also assists in controlling a structures' ageing. Information such as this can assist in developing new life cycle models for bridges.

The short term benefits may not gravitate towards the use of SHMS because of their higher capital costs, but the long term risk (e.g. Loss of life, financial, reputational, etc.) benefits of SHMS outweigh current BMS methods which rely on the accuracy of the visual inspection and maintenance. Infrastructure is ageing and there is also increased utilisation. Bridge engineering is a specialised field and often companies and expertise are sought from outside South Africa. The skills required for bridge engineering entail years of experience and constant practice in the field, thus there is a high demand for bridge engineers in the country.

Unfortunately, this makes it difficult to find qualified inspectors to conduct condition assessments required for bridge management.

If skills transfer continues to be a challenge in the country, this will pose an even bigger problem for the management of bridges. Not only will the practice become more expensive, but also the shortage of inspectors will become even bigger. SHMS eliminate this challenge. As computer software for SHMS becomes more sophisticated, there will be an even lesser need for human intervention in the bridge asset management process.

CHAPTER 4

4 METHODOLOGY

4.1 Introduction

The purpose of this chapter is to establish the methodology that is to be used in achieving the research objectives. The chapter will revisit the primary and secondary objectives, it will then describe the research design, data analysis and a conclusion will be deduced.

4.2 Primary Objective

The primary objective is to establish the economic value of using Structural Health Monitoring Systems in South Africa as a way of dealing with the maintenance backlog that exists in the country with regards to bridge structures.

4.3 Secondary Objective

The secondary objective is to establish whether value is best found only from the installation of SHMS for monitoring or SHMS cast in-situ for internal damage assessments or both. The distinction was explained in Chapter 3.

4.4 Research Design

Although a case study is used for the research, the research design is based on a mixed method approach with qualitative and quantitative elements. Case study research is one of the 6 types of research design methods that are often discussed in research literature (Maree, 2007). Qualitative is often described as research that attempts to collect rich descriptive data in respect of a particular phenomenon or context with the intention of developing an understanding of what is being observed or studied. This is different to quantitative research, which is more scientific.

The data used in the research is classified as secondary data as it was obtained from Transnet Freight Rail's (TFR) bridge division records. Pellissier (2007) describes secondary data as data already collected by other researchers as well as through extensive consultation of literature. Primary data is data that is collected entirely by the researcher. The case study used assists in realising scenarios that may be difficult to explain. From the case study the decision on whether or not there is economic value in using SHMS over current BMSs, may be validated.

4.5 Sampling Design

There are 185 bridges on the Ermelo-Richards Bay line and data of all 185 bridges was obtained from TFR. However, only a sample of 22 were used to determine economic value. The data shown in Table 7 were first divided into different sections of the line. In trying to establish possible causes of interruptions that could occur on the line, the data were first refined into whether there would be an alternate route or not. Secondly, from the data obtained, the columns with the most information in the columns were selected. Thirdly, in each section of the line, the longest and shortest overall bridge lengths with the most and least spans and the type of feature crossed and carried was equally represented. The age of the bridge was also taken into consideration. The oldest and most recently built bridges in each section were selected, the type of bridge and the number of lines of the bridge were a final deciding factor.

The sampled bridges were determined by the type of feature that they cross over or under, impact on the rail production and amount of time they would take to repair in the event of a collapse or a need for a large repair.

4.6 Data Collection Method

A request sheet was sent to TFR for the data required to fulfil the case study. The information sought on the spreadsheet included: The types of bridges on the line, the type of line (single or double), what feature the bridges cross over, the number of spans of each bridge, the year that each bridge was built, the frequency of inspections, bridge usage and the type of inspections conducted on the bridges. See Appendix C. An interview was conducted with the Chief Engineer for the Eastern Region Mr Tshilidzi Munyai on the operations of the Ermelo to Richards Bay coal line.

4.7 Data Analysis.

It was established that most of the bridges were constructed in the late 1960’s, all the bridges are now concrete and they are inspected annually using the MICA (Manual for Infrastructure Condition Assessment) system of inspection. The bridge usage is daily and most bridges cross over rivers. Although TFR runs a 24-hour operation, some lanes are occasionally closed for rail maintenance during shutdown.

CHAPTER 5

5 CASE STUDY

5.1 Introduction

There are various philosophies on the characteristics of a qualitative case study. Two worth noting that are in line with this particular research are from Guba and Lincoln (1981) and Helmstadter (1970). The former characterise a case study that has a thick description, is grounded, holistic and lifelike, illuminates meaning and builds on tacit knowledge. Helmstadter (1970) characterises case studies that can be used to remedy or improve practice, results are a hypothesis, design is flexible and it can be applied to troubled situations. This case study follows the latter objective. In establishing whether or not there is economic value in the use of SHMS, a recommendation of their implementation will improve the challenge of maintenance in infrastructure assets. If proven to have value and the design models are flexible, then road bridges could also be evaluated for SHM implementation. The issue of maintenance deferral is indeed a troubled situation which requires creative solutions. The case study is categorised in the single concept/single incident option i.e. finding value and making use of the coal line in order to do this.

TABLE 9: Case Study Structure – An options matrix (Source: Helmstadter, 1970)

Single Concept Single Incident	Multiple Concept Single Incident
Single Concept Multiple Incident	Multiple Concept Multiple Incident

For the purposes of the case study, the research questions need to be re-evaluated:

a) Is there economic value in using SHMS?
b) If there is value in installing SHMS, does the benefit come best from the installation on an existing structure or embedded within structures?

5.2 Background

The coal line from Ermelo to Richards Bay is owned by rail operator Transnet Freight Rail (TFR) which employs 25 000 people throughout South Africa, making freight rail the largest division of Transnet. The line begins in the northern part of the country in Lephalale and services 44 coal mines. The focus however will be on the southern part of the line from Ermelo to Richards Bay.

The Rail specification: The distance of this route is 588km. This line section is a double track with the exception of the Overvaal Tunnel which is currently a single line (TFR, 2015). The double line carries 26tons/axle and has a 25kV AC overhead line. The sharpest curve radius is 550m and the steepest gradient is 1:160. This line carries mainly heavy haul traffic with some general freight and train sizes of medium to heavy. The maximum speed permitted by the trains is 80km/h. The line was opened to traffic on the 1st of April 1976 by the SA Railways and Harbours Administration (Du Toit, 1976). The line is plagued by power supply constraints and frequent outages, resulting in operational delays. The power constraints also impose restrictions on train scheduling and contribute to train delays. As mentioned above, the Overvaal Tunnel has a single track section and this limits the capacity of the line to 16 No. 200-wagon trains per day.

Strategic Integrated Projects (SIPs) were identified by Transnet as a State Owned Enterprise (SOE) in order to participate in the Presidential Infrastructure Coordinating Committee (PICC). SIP 1 pertains to the TFR coal line from Lephalale to Richards Bay. The aim is to unlock the northern mineral belt with Waterberg as the catalyst. This will include the South African coal transportation system development, export coal line, Waterberg link development, Swazi rail link, coal backbone capacity and Eskom road-to-rail migration plan (TFR, 2015).

Delays in operations on the TFR line as noted above have resulted in a lesser production and export of coal than the line is capable of transporting. The planned expansion is the reason for using this particular line as a case study. Identified as a major income generator and economic contributor to the country, it is an ideal tool that can be used to establish economic value.

The civil infrastructure (focus on bridges) forms the backbone of the line thus needs to be maintained in order to keep the line operational.

As previously stated there are 185 bridges along the route from Ermelo to the Richards Bay Coal Terminal (RBCT). These bridges are predominantly reinforced concrete structures and span over rivers and roads. The longest bridge on this route is the uMfolozi River Bridge which is a 487m long arched continuous bridge. The number of bridges in each construction period (5 years) is compiled in a graph using the bridge data obtained from TFR, (shown in Figure 5-1).

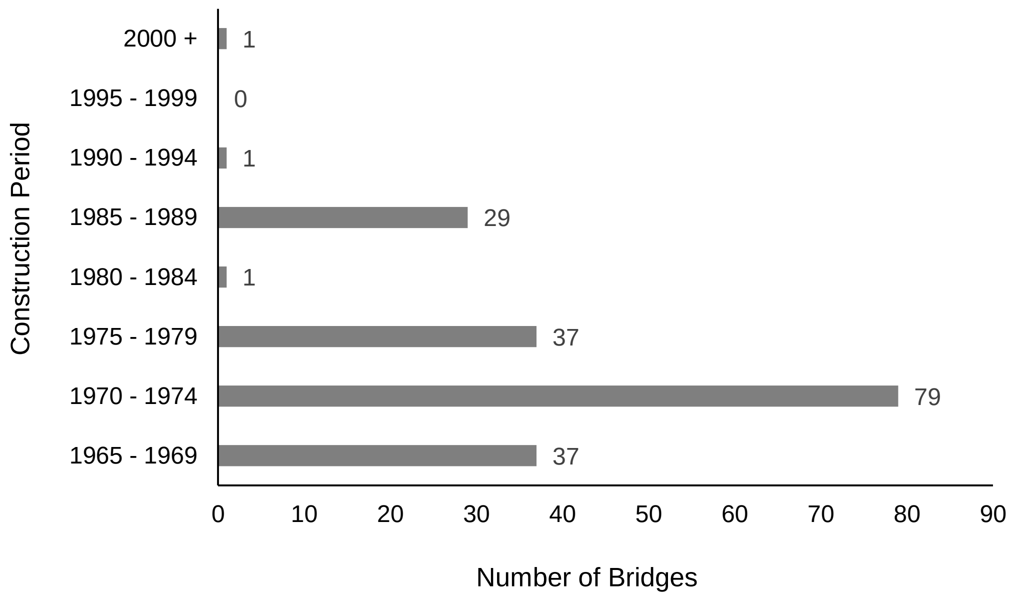


FIGURE 5-1: The Number of Bridges constructed in each period on the Transnet Freight Rail coal line from Ermelo to Richards Bay (Source: Transnet Freight Rail).

A total of 62.7% (constructed between 1965 and 1974) of the bridges on the coal line from Ermelo to Richards Bay are expected to reach their design life at the same time. If it is assumed that they are currently not being maintained across the board, then a similar deterioration rate can be expected (with the exception of those closest to the coast, which may deteriorate faster), leading to these bridges reaching the EUL at the same time. Planning is thus essential, in order to yield optimum decision making. The result of simultaneous degradation is high costs of rehabilitation or asset replacement. In installing SHMS from the creation or acquisition stage of the asset's life, 6 out of 8 of the elements in the lifecycle are addressed. The model in Figure 3-3 is modified in Figure 3-4 to address this.

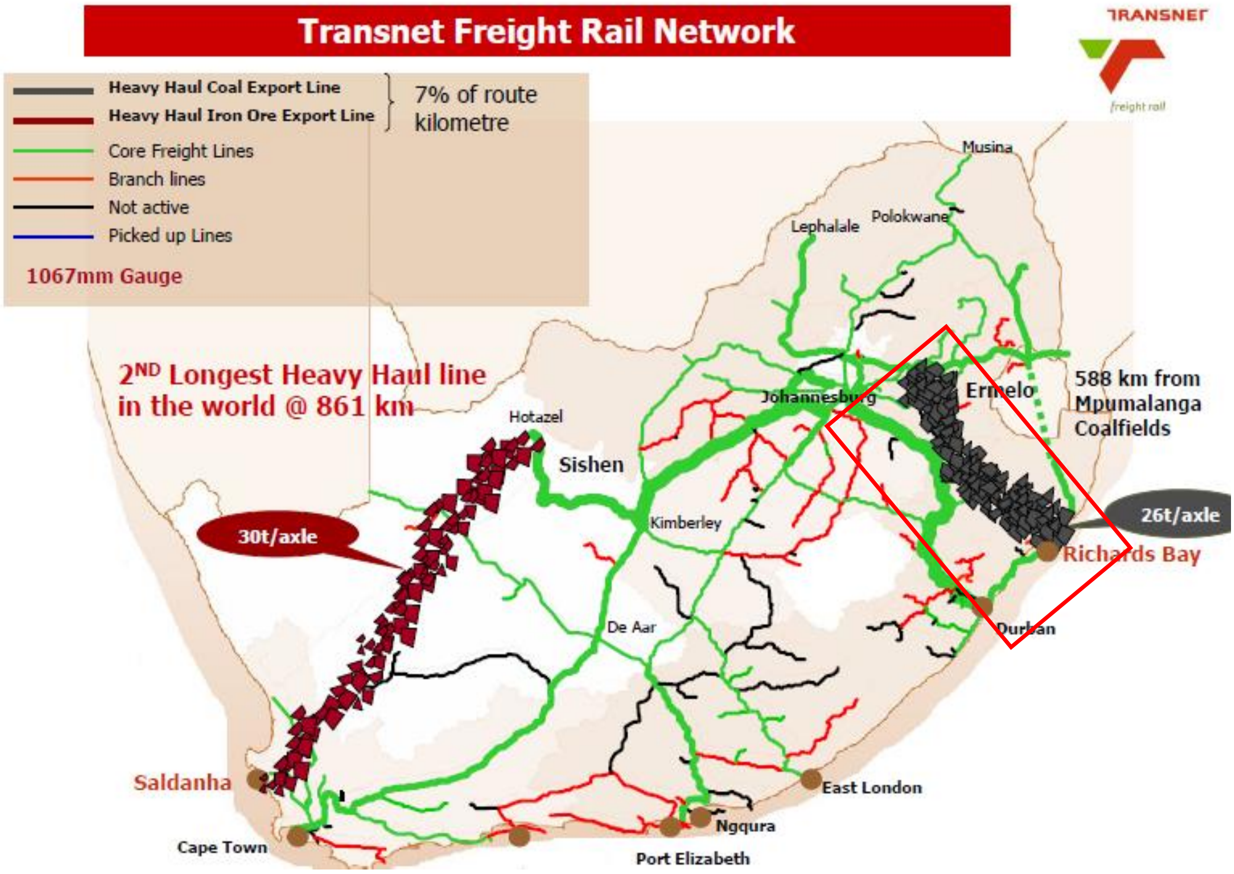


FIGURE 5-2: Line Profile from Ermelo to Richards Bay (Source: Kuys, 2011)

5.2.1 The track profile

The track is constructed for two-way working and is managed at three remote control centres i.e. Ermelo, Vryheid and Richards Bay. Trains from the northern portion of Ermelo run at a headway of 15 minutes, enabling 62 trains to be run daily. This is a 3kV DC line. In addition to the 100-car trains the line also operates empty 200-wagon trains.

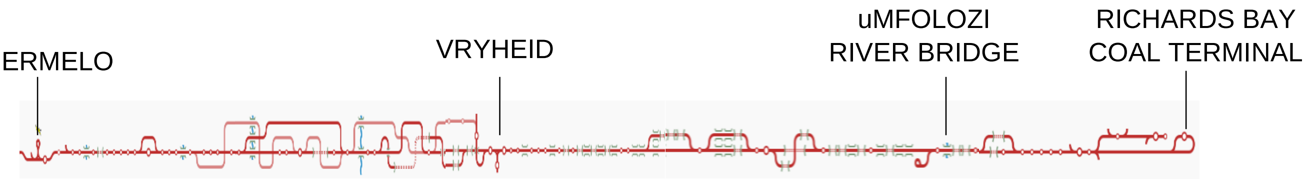


FIGURE 5-3: Profile of railway line from Ermelo to the Richards Bay Coal Terminal

On the Ermelo-Richards Bay coal line, half of the capacity is reserved for coal trains and the other half is used by the rest of the freight trains. TFR transports on average about 230 000 tons of coal daily on this line. Only 16 coal trains and 13 freight trains of other commodities can go through the tunnel because of the tunnel's single track. Currently breakdowns in the tunnel halt operations in this area. TFR has embarked on a R91 billion expansion project to address this problem. On the border of Mpumalanga and Kwazulu-Natal the railway track of the two-lane track divides for the first time into a track for the descending trains and a route for the trains traveling uphill.

The two tracks cross on separate bridges on the border of the Phongolo River and meet after the 30 km turn at Mahulumbe south of Paulpietersburg. In Mqwabe the paths separate again in a lane for uphill and one for downhill moving trains, where the paths on the 30 km long section to Vryheid cross three times. The uMfolozi River route (The uMfolozi River bridge is show in Figure 5-5) follows after Vryheid on the northern side of the valley until it changes to Engolothi on the southern side of the valley before reaching Richards Bay.

a) Ermelo – Piet Retief

The Ermelo operating station is located south of the town and serves mainly the traction change from direct to alternating current and the combination of the 100-car trains to 200-wagon trains while traveling south as well as the reverse operations when driving north. The line consists of four track fields and a loop at Iswepe to join the double fields.

Trains from the south that enter group b, are pulled through the loop by means of a shunting locomotive after the decoupling of the locomotive.

There are 30 bridges on this line section, but a sample of 5 has been taken for the purposes of this study. The information regarding construction dates was largely missing from the bridges on this line section, but the data found shows that the oldest bridge was constructed in 1967. For the purpose of this study it will be assumed that this is the oldest date.

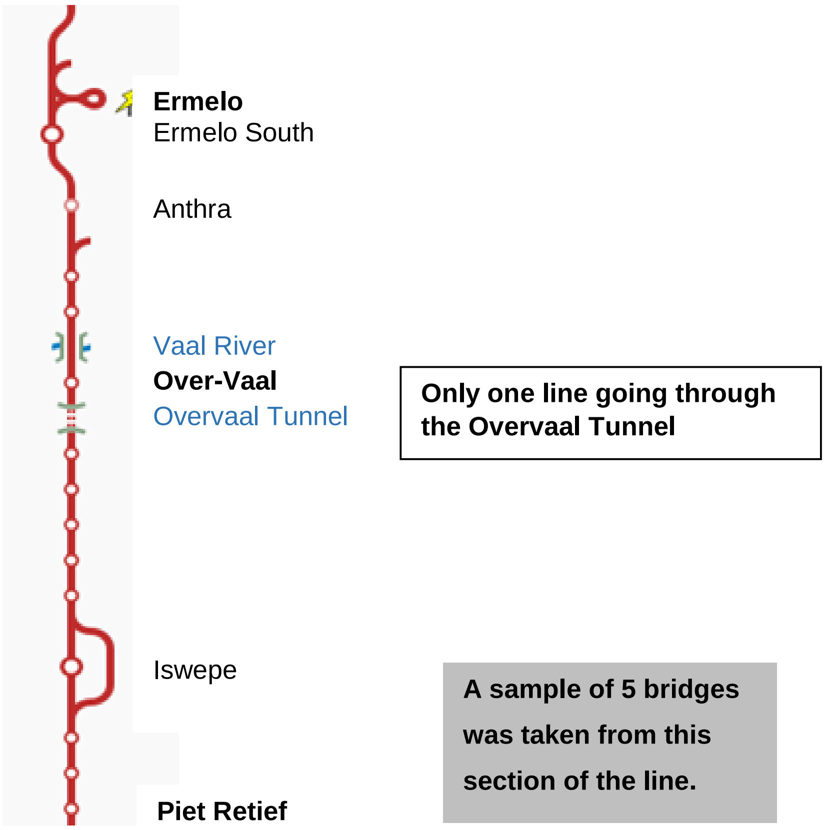


FIGURE 5-4: Line section from Ermelo to Piet Retief (Transnet Freight Rail)

b) Piet Retief – Vryheid East

There are two lines electrified with 3 kV DC line from Newcastle and the 25 kV AC line. Vryheid contains two marshalling yards, i.e. Vryheid East and Sikame (which receives coal deliveries from Hlobane). Along this route are 57 bridges, but a sample of 7 has been taken for this line section. The oldest bridge in this line section was built in 1968, the line runs through tunnels and serves as a rail-over-rivers.

c) Vryheid East – Richards Bay Coal Terminal (RBCT)

There are 87 bridges on this section of line. The oldest bridge in this line section was built in 1968.

The line terminates at the RBCT which is crucial to the operations of the line and a gateway to exporting. RBCT is equipped with state-of-the-art machinery, is able to handle large shipments and has gained a reputation for operating efficiently and reliably in order to prevent demurrages. The coal terminal consists of a quay 2.2 kilometres long with 6 berths and four ship loaders, the two largest of which load at 10 000 and 12 000 tons per hour. RBCT offloads wagons at a rate of 5 500 tons per hour. Using this rate, 100 wagons can be offloaded in under two hours (RBCT, 2016).

The coal stockyard has a capacity of 8.2 million tons with 36 grades of coal stacked in more than 92 stock piles. Once loaded, the ship and its cargo is placed in the hands of Transnet National Ports Authority, which coordinates the arrival and departure of over 700 ships each year (RBCT, 2016).

5.3 Rail maintenance

The cost of shutting down the coal line can run into hundreds of millions of Rands (RBCT, 2016). The system currently has a contracted capacity on the coal line to RBCT, which is 81 million tons per annum and TFR expects to move 76 million tons for the financial year 2016/2017. Data obtained from Transnet Freight Rail revealed that the bridges along the line sections are visually inspected annually, however, after interviewing the asset managers they highlight that maintenance to bridges is often deferred.

There are currently no existing SHMS on the bridges. There are however rail sensors that have been installed to monitor any defects arising from the railway tracks. The activities carried out during this maintenance period included among others, screening (cleaning and removal of obsolete ballast stones), sub stations overhaul which includes, among others, repairing oil leaks on main transformers, repairing oil leaks on primary circuit breakers, filter oil of main transformers, etc. Very little with effects to the structural maintenance of the bridges was conducted.

The total shutdown programme is necessitated by the fact that on the coal line there are sections where infrastructure work cannot be carried out without stopping the entire train service. Operational disruptions can cost the company hundreds of millions in revenue (the revenue from coal is calculated in Table 12 in Chapter 6), therefore TFR tries to avoid operational disruptions during maintenance periods as this will also interfere with mining operations from where TFR obtains its commodities.

The oldest bridge constructed along this track was constructed in 1968 and the longest bridge is the uMfolozi River Bridge, a reinforced concrete arch bridge (See Figure 5-5):

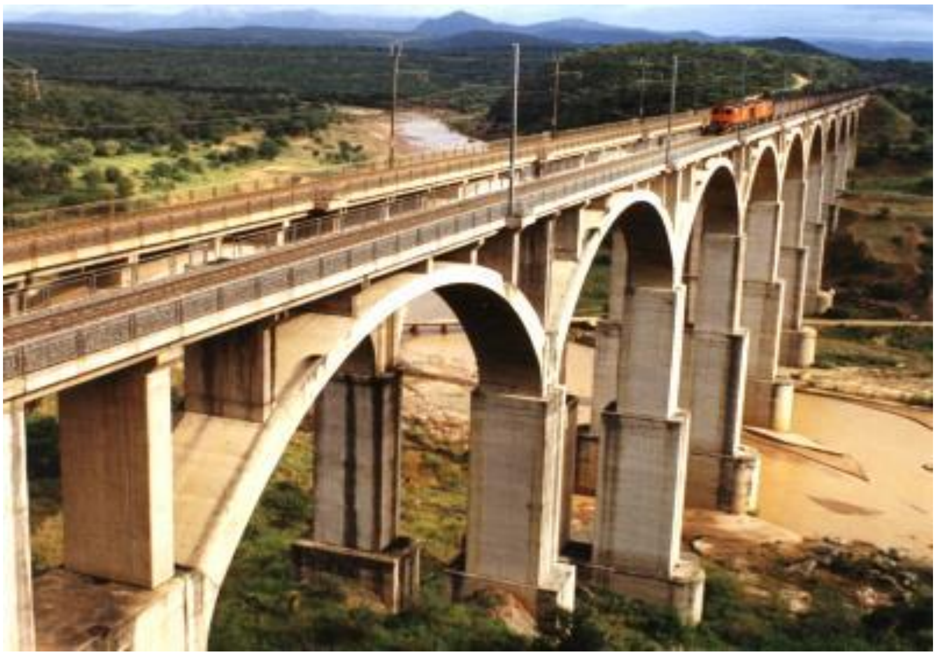


FIGURE 5-5: uMfolozi River Rail bridge (Source: http://www.railwaygazette.com, 2013)

5.4 Summary

Transnet Freight Rail is the largest rail operator in the country. It is imperative that their infrastructure remains in a safe-to-use condition. Delays could not be determined and losses as a result of these did not form part of the scope of the study.

A cost study needs to be conducted using the sampled bridges on the rail network of:

- The Current Replacement Costs and Depreciated Replacement Costs to establish what the cost would be in replacing the bridges.
- The bridge systems most suitable for the cost.
- The Net Present Value of the bridges, in order to make decisions about the future of the bridges.
- The estimated cost of installing sensors for each bridge.
- The income from coal exports to rate the importance of the bridges on this line.
- The cost of Bridge Management inspections.

Value can be established through various means. In this case it will be based on the cost benefit on a macro-economic level, the cost comparison between SHMS and BMS, the extent to which risk can be mitigated when using SHMS vs when conducting visual inspection, as well as by looking at SHMS through the prism of Depreciated Replacement Cost. The data in Table 10 of the bridges, were obtained from TFR.

TABLE 10: Bridge Data

BRIDGE DATA (Sampled from the Ermelo to Richards Bay coal Line)									
Line Section	**Bridge Description**	**Type of Bridge**	**Lines at Bridge**	**Feature Crossed**	**Overall Length**	**No. of Spans**	**Type of Inspection**	**Year Built**	**Alternative Route**
Ermelo - Piet Retief (Sample: 5)	Rail over road bridge (A)	Unknown	1+2	Railway	Uknown	Uknown	MICA	1973	Yes
	Rail over road bridge 3540 (1974)	Unknown	1+2	Railway	Unknown	Uknown	MICA	1974	Yes
	Road over rail bridge	Unknown	1+2	Road	Unknown	Uknown	MICA	1967	Yes
	Road over rail bridge near Kemp Siding 3542 (1973)	Unknown	1+2	Road	Uknown	Uknown	MICA	1973	Yes
	Rail over road bridge 2480 (1973)	Unknown	1+2	Railway	Unknown	Uknown	MICA	1973	Yes
Piet Retief - Sikame (Sample: 5)	Rail/Road RC Bridge	Simply Supported	1+2	Road	15.15	1	MICA	1972	Yes
	Road over Rail RC Bridge	Continuous	1+2	Railway	35.78	3	MICA	1975	Yes
	RC Viaduct	Continuous	1+2	River	480.00	12	MICA	1972	Yes
	RC Viaduct	Continuous	1+2	River	165.00	5	MICA	1972	Yes
	RC Viaduct	Continuous	1	River	400.00	10	MICA	1984	No
Sikame - Vryheid East (Sample: 2)	Open ribbed spandrel RC Bridge	Continuous	1+2	River	109.73	4	MICA	1968	Yes
	Rail over road RC Bridge	Simply Supported	1+2	Road	15.40	1	MICA	1969	Yes
Vryheid - Richards Bay (Sample:10)	OH Road Bridge	Continuous	2	Railway	35.66	3	MICA	1969	No
	RC Arched Bridge	Open Spandrel Arch	1	River	130.45	5	MICA	1969	No
	RC Bridge	Continuous	2	River	99.06	5	MICA	1969	No
	RC Arched Bridge	Open Spandrel Arch	1	River	603.50	18	MICA	1985	No
	RC Arched Bridge	Open Spandrel Arch	2	River	259.69	6	MICA	1970	No
	RC Arched Bridge	Open Spandrel Arch	1	River	110.00	4	MICA	1987	No
	RC Arched Bridge	Open Spandrel Arch	2	River	152.40	5	MICA	1970	No
	RC Bridge	Continuous	2	River	164.50	8	MICA	1976	No
	RC Bridge	Continuous	1	River	120.00	3	MICA	1987	No
	RC Bridge	Continuous	2	River	119.05	6	MICA	1976	No

CHAPTER 6

6 COST ANALYSIS AND DISCUSSION

6.1 Introduction

In assessing the economic value of using SHMS on South African bridges it was important to take cognisance of the questions posed in Section 1.3 of this dissertation. The questions that needed to be addressed looked at: To what extent are current BMSs effective in the safe monitoring of structures, the effectiveness of routine maintenance, whether BMS in its current format can ever fully be disposed of, what constitutes the economic value of SHMS and whether there is space for autonomous devices in the industry as a means of bridge management.

In establishing the value of using SHMS, the costs associated with them need to be defined. Defining the cost solution for a Structural Health Monitoring System required for each bridge requires understanding the complexities of the individual bridges first. For the purposes of this study where a cost comparison between SHMS and BMS needs to be made to try to establish value, an assumption will be made based on the main costs associated with the implementation of a SHMS. There is a capital investment that needs to be made which includes SHMS design costs, hardware costs, installation costs and the costs for installation reporting, as-built documentation and system manuals (Inaudi, 2011). The operational costs include: System maintenance (spare parts, consumables; energy and communication costs), data management costs and data analysis (interpretation and reporting costs).

6.2 SHM Costs

The highlights of soft and hard benefits were discussed in Chapter 2. The cost of the SHMS required depends on the solution required on the bridge. Different types of systems, the quantity required and the costs associated with them are discussed below. The development of sensors such as the MEMS accelerometer (Shown in Figure 2-15) have revolutionised their application, making them smaller, lower powered and easily integrated into a wide range of applications.

6.2.1 Accelerometers

An accelerometer is an electromechanical device that can measure both static (gravity) and dynamic (motion or vibration) accelerations. Depending on the manufacturer and the sensitivity, the cost of the MEMS accelerometer can cost from about $10 to $1650 (US).

6.2.2 Senspot sensors

The costs of sensors vary tremendously. Senspot sensors are said to provide a practical, low cost option for the challenge of remote bridge health monitoring. Small quantity production costs are about $150 - $200 per device. When produced in quantities of about 10 000 or more the cost is projected to drop to below $50. Quick (2011) estimates an average-sized highway bridge to need about 500 sensors at a cost of $20 a unit.

The sensing system on the St. Anthony Falls Bridge in the US cost about $1 million, it consisted of: 500 off-the-shelf sensors. Structural deformations are measured by 195 vibrating wire strain gauges, 24 resistive strain gauges and 12 fibre optic displacement sensors; 243 thermistors measure temperatures and 26 accelerometers measuring modal frequencies to calculate deflections and structural vibrations. This averages to about $2 000/sensor. The Bill Emerson Memorial Bridge in Missouri is instrumented with 84 accelerometer channels with an average cost per channel of over $15 000 (Rice and Spencer, 2009).

Embedded computers with wireless communication capability cost in the order of $200 per node. CAR (2012) estimate the cost of sensing systems to range from $5 000 to $200 000. The costs include collection costs, costs for data storage, operational costs, lane or closure costs, labour costs and service fees contractors charge per bridge.

FIGURE 6-1: Senspot sensors for humidity, tilt, crack and strain monitoring (Source: Kalantari and Mirbaghen, 2012).

6.3 BMS Costs

Table 5 in Chapter 2 shows that SANRAL inspection rates can be estimated to cost about R6500 per bridge. If the same bridges are to be inspected in 5 year cycles for an estimated useful life of 80 years, 16 inspections are expected to take place during each bridge's lifetime.

A full cost analysis is conducted in Chapter 7.

6.4 Replacement Costs

The section from Ermelo to Piet Retief will be excluded for the purposes of this study due to insufficient information. Table 5 in Chapter 2 details the cost effective bridge system per square metre which gives R15 000 for span lengths of 6 to 15m, R20 000 for span lengths between 15 and 30m and R25 000 and R30 000 for the respective box girders. However, there are other variables to the costs that have not been included such as the ground conditions and foundation types which have the potential to alter the cost significantly, thus the cost/m^2 rate is regarded only as a high level estimate. If the bridges in Chapter 5 (Table 10) are used to cost for full replacement (CRC), the values for each bridge is calculated in Table 11 using the unit rates in Table 5.

TABLE 11: Current Cost Replacement of Bridges

BRIDGE DATA (Sampled from the Ermelo to Richards Bay coal Line) **1, 2 or 1 + 2 denote Line 1, Line 2 or Lines 1 and 2 respectively									
Line Section	**Bridge Description (Year Built)**	**Type of Bridge (No. of Spans)**	**Lines at Bridge**	**Feature Crossed**	**Overall Length**	**Width (m)**	**Area (m^2)**	**Unit Rate (R/m^2)**	**CRC (R million)**
Piet Retief - Sikame (Sample: 5)	Rail/Road RC Bridge (1972)	Simply Supported (1)	1+2	Road	15.15	6.65	100.75	15 000	3
	Road over Rail RC Bridge (1975)	Continuous (3)	1+2	Railway	35.78	6.65	237.94	30 000	14
	RC Viaduct (1972)	Continuous (12)	1+2	River	480.00	6.65	3192.00	30 000	192
	RC Viaduct (1972)	Continuous (5)	1+2	River	165.00	6.65	1097.25	30 000	66
	RC Viaduct (1984)	Continuous (10)	1	River	400.00	6.65	2660.00	30 000	80
Sikame - Vryheid East (Sample: 2)	Open ribbed Spandrel (1968)	Continuous (4)	1+2	River	109.73	6.65	729.70	30 000	43
	Rail over road RC Bridge (1969)	Simply Supported (1)	1+2	Road	15.40	6.65	102.41	15 000	3
Vryheid - Richards Bay (Sample:10)	OH Road Bridge (1969)	Continuous (3)	2	Railway	35.66	6.65	237.14	30 000	7
	RC Arched Bridge (1969)	Open Spandrel Arch (5)	1	River	130.45	6.65	867.49	30 000	26
	RC Bridge (1969)	Continuous (5)	2	River	99.06	6.65	658.75	30 000	20
	RC Arched Bridge (1985)	Open Spandrel Arch (18)	1	River	603.50	6.65	4013.28	30 000	120
	RC Arched Bridge (1970)	Open Spandrel Arch (6)	2	River	259.69	6.65	1726.94	30 000	52
	RC Arched Bridge (1987)	Open Spandrel Arch (4)	1	River	110.00	6.65	731.5	30 000	22
	RC Arched Bridge (1970)	Open Spandrel Arch (5)	2	River	152.40	6.65	1013.46	30 000	30
	RC Bridge (1976)	Continuous (8)	2	River	164.50	6.65	1093.93	30 000	33
	RC Bridge	Continuous (3)	1	River	120.00	6.65	798.00	30 000	24
	RC Bridge	Continuous (6)	2	River	119.05	6.65	791.68	30 000	24
								Total (Rand million)	759

Bridge monitoring is based on the following three valuations. It is a function of its financial reporting requirements, asset valuation regime and asset management requirements. The following organogram illustrates these functions:

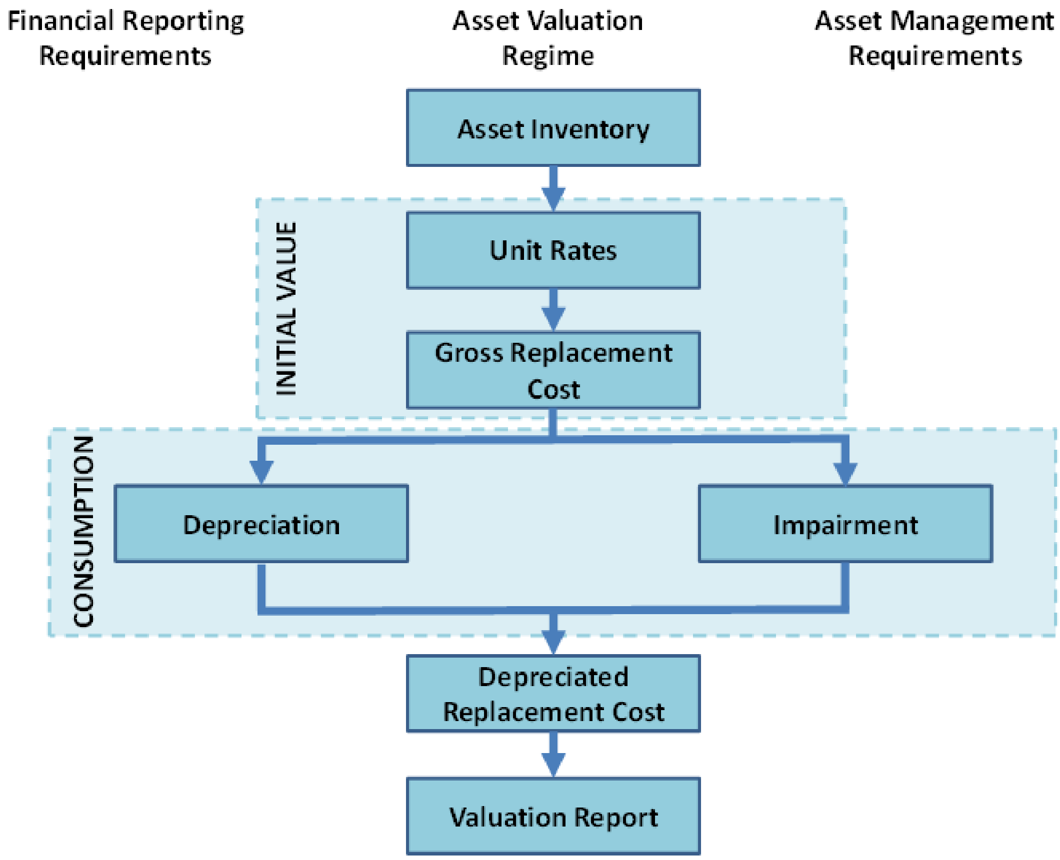


FIGURE 6-2: Asset Valuation (Source: COTO, 2013c)

An asset evaluation will be conducted on the sampled bridges. The inventory information is known and the number and costs of sensors needs to be established and compared with current BMS.

It must be noted that none of these sensors can be assessed with embedded nodes as the bridges are all existing. It will be assumed that the cost of a wireless network system will cost in the region of $600 per node. The viability per bridge is then assessed in each table. For the purposes of uniformity in currency, the Rand will be used with a January 2017 R/$ exchange rate of R13.50 = 1 US$.

Bridges 6-15m long are regarded as small bridges, 15-30m average and 30-500m are large bridges. What is required from a sensing system is: a sensing interface, a computing core, a wireless transceiver, and a power source. The autonomous data acquisition nodes consist of structural sensing elements e.g. strain gauges, accelerometers, linear voltage displacement transducers, inclinometers, among others (Zhou and Yi, 2013). Assuming a 100mm range per sensor for short gauge sensing, the sensor costs that would be required on each bridge and the costs of the sensors as a percentage of CRC and DRC are calculated in Appendix A.

6.5 Income generated from the Coal line

On average TFR transports 230 000 metric tonnes per day (TFR, 2016). The price of coal per metric tonne for 2016 is as shown in Table 12. This table shows the estimated coal transported by TFR in 2016 and the income generated from these exports.

TABLE 12: Total Income from coal exports (Source: http://www.indexmundi.com)

MONTH	PRICE/Metric Ton	Tonnes Transported per day	Number of Days in month	Tonnes Transported per month	Income (R million)
Jan-16	817.11	230 000	31	7130000	5 826
Feb-16	811.77	230 000	29	6670000	5 415
Mar-16	819.74	230 000	31	7130000	5 845
Apr-16	771.19	230 000	30	6900000	5 321
May-16	829.75	230 000	31	7130000	5 916
Jun-16	869.75	230 000	30	6900000	6 001
Jul-16	899.87	230 000	31	7130000	6 416
Aug-16	905.25	230 000	31	7130000	6 454
Sep-16	944.73	230 000	30	6900000	6 519
Oct-16	1166.91	230 000	31	7130000	8 320
Nov-16	1243.53	230 000	30	6900000	8 580
Dec-16	1136.14	230 000	31	7130000	8 101
			Total	84 180 000	R 78 714

On average TFR exported 84.18 million tons per year and generated R78,7 billion from this export. The current replacement cost of the bridges that are likely to cause impact is R759,2 million, the total depreciated replacement cost of these bridges is: R358,8 million. The CRC constitutes 0.96% of TFR's annual revenue from coal, but these bridges only constitute 9.1% of the total number of bridges sampled. Using formula 2.3, the NPV for each bridge is shown in Table 13.

TABLE 13: The Net Present Value of the bridges

Line Section	Bridge	CRC (R)	NPV (R)
Piet Retief - Sikame (Sample: 5)	Rail/Road RC Bridge	3 022 500.00	393 243.02
	Road over Rail RC Bridge	14 276 400.00	1 559 537.52
	RC Viaduct	191 520 000.00	24 917 751.41
	RC Viaduct	65 835 000.00	8 565 477.05
	RC Viaduct	79 800 000.00	5 159 732.94
Sikame - Vryheid East (Sample: 2)	Open ribbed spandrel RC Bridge	43 782 000.00	7 191 405.43
	Rail over road RC Bridge	3 072 300.00	476 075.61
Vryheid - Richards Bay (Sample:10)	OH Road Bridge	7 114 200.00	1 102 397.91
	RC Arched Bridge	26 024 700.00	4 032 719.76
	RC Bridge	19 762 500.00	3 062 345.55
	RC Arched Bridge	120 398 400.00	7 344 110.16
	RC Arched Bridge	51 808 200.00	7 573 645.09
	RC Arched Bridge	21 945 000.00	1 191 358.10
	RC Arched Bridge	30 403 800.00	4 444 616.70
	RC Bridge	32 817 900.00	3 382 065.72
	RC Bridge	23 940 000.00	1 299 663.38
	RC Bridge	23 750 400.00	2 447 609.80

TABLE 14: Bridge Inspection costs to EUL at year 80.

YEAR	Year 40	Year 45	Year 50	Year 55	Year 60
Inspection Costs	R 6500.00	R 6886.58	R 7144.40	R 7411.87	R 7689.35
YEAR	Year 65	Year 70	Year 75	Year 80	
Inspection Costs	R 7977.22	R 8275.87	R 8585.70	R 8907.13	
Sum of Inspection Costs		R 69 378.12			

Bridge inspection costs in Table 14 have been estimated using an annual inflation rate of 5.9% (this is based on South Africa's current linked inflation rate) until the EUL of the bridge is reached. The estimated cost of conducting a bridge inspection in the 80th year will be R8 907.13, if this inflation rate is assumed to remain constant. This gives that the cost of conducting bridge inspections will be R69 378.12 per bridge if the bridge is in its 40th year in 2016, for its RUL.

i) If the inspection cost per bridge is a percentage of the Net Present value of the *lowest* costed bridge, then:

Inspection costs as a percentage of NPV = (R69 378.12 / R393 243.02) x 100 = 17.6%

The inspection costs would make up 17.6% of the value of the structure for the remaining life of the structure.

ii) If the inspection cost per bridge is a percentage of the Net Present value of the *highest* costed bridge is taken:

Inspection costs as a percentage of NPV = (R69 378.12 / R24 917 751.41) x 100 = 0.28%

The inspection costs would for the remaining life of the structure, make up 0.28% of the value of the structure. It therefore gives that the shorter spanned bridges become more expensive to inspect over time. It must however be noted that the inspection rate is dependent on the size of the bridge and may vary, thus this statement is only theoretical.

If the sensor costs for the same bridge (lowest costed bridge) which was calculated at R1 231 200.00 is taken and the NPV of this cost is calculated using formula 2.4, the value equals R124 305.46

iii) If the sensor cost for this bridge is a percentage of the Net Present value of the *lowest* costed bridge is taken:

Sensor costs as a percentage of NPV = (R124 305.46/ R393 243.02)) x 100 = 31.6%

The sensor costs if installed in the 40th year would for the remaining life of the structure, make up 31.6% of the value of the structure.

This is almost double what it would cost using the current method of monitoring bridges. There are other variables that need to be taken into consideration, among these the potential loss of income potential in the event of failure. In this particular case study income from exports of coal amounted to R 78,7 billion which is a significant amount of GDP income. The direct cost comparison can therefore not be viewed in isolation. One of the definitions of value given in chapter 3 was the measure of benefit provided by a good or service, thus any disruptions in the ability to provide the required level of service poses various risks. Risk is a crucial component in the management of critical assets.

CHAPTER 7

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

To assess the economic value of SHMS, a study was conducted on the Transnet Freight Rail coal line from Ermelo to Richards Bay. The objectives of the research were to evaluate the economic value of using Structural Health Monitoring Systems (SHMS) on bridges in South Africa as a way of dealing with the maintenance backlog in the country. In addition to this, the secondary objective was to find out whether value, if established from SHMS, is best found only from the installation of SHMS for monitoring or SHMS cast in-situ for internal damage assessments or both. Also, can condition assessments be completely eliminated from the BMS process and finally it looks at the future of BMS in South Africa.

17 bridges from the 185 bridges on the coal line were sampled. One of the reasons why the coal line was selected was because of the annual approximate estimated income of R78,7 billion in 2016 from transporting 84.1 million tons of coal for export from the Richards Bay coal terminal. This accounted for 1.8 % of GDP in 2016 (GDP was at R 4.293 trillion) which makes the coal line bridges important in that without them disturbances could impact the income generation from coal exports and other commodities.

Structures face increased utilisation, they are ageing and are exposed to harsh environments (especially near the coast). In a review that was conducted on current bridge management systems the advancements and shortcomings were assessed, but highlighted that Bridge Management (BMS or SHM) play a crucial role in the sustainability of structures. The assessment though, was to determine the economic viability of implementing SHMS on South African bridges as a means of preventative maintenance. In doing so the following questions were explored:

- The benefit obtained from the bridge serving its purpose
- The value of the bridge at any given time through its life cycle
- A comparison between current BMS and using SHMS for monitoring.

7.1.1 The benefit obtained from the bridge serving its purpose

A study of the Ermelo to Richards Bay line revealed that a large percentage of these bridges were constructed in the period from 1965 to 1974. This means that 20% of them are envisaged to reach their expected useful life in the year 2045 and an additional 42.7% of them in 2050. According to life cycle models however, the first 20% of bridges have aged past 50% of their design life. Interruptions and infrastructure bottlenecks still cause delays in the transportation of coal, given the 24-hour operation it is important that the bridges remain in a safe-to-use condition. In 2015 mining and quarrying contributed 7.7% to South Africa's GDP, thus the export of minerals forms part of the 11 major sectors of the economy. South Africa still holds 3.4% of the world's reserves of coal and is the 7th largest exporter of this commodity. This highlights the importance of taking care of the infrastructure that enables the operations of a major income generator such as the TFR line. It also suggests that there is a quantifiable economic benefit from investing in the maintenance of the infrastructure of this line.

Due to a decline in the investment in infrastructure, maintenance is circumvented due to limited budgets and not given a priority over new infrastructure. While new infrastructure is required, neglecting old infrastructure leads to a rapid deterioration of the asset. Once assets reach a certain level of deterioration they can no longer be repaired and need to be replaced. South Africa with its global standing in coal reserves and as a major exporter has over the years increased the load of coal on their trains. Whether over-loading on the bridges has been taken into account, could not be established.

TFR conducts what is called a MICA inspection for the monitoring of its bridges, which places the responsibility solely on visual inspections which reviewers of BMS deem not be adequate for the determination of the extent of defects on structures. A lot of the bridges are not located on major roads where people frequent, thus it is essentially reliant on the annual MICA inspection by the bridge department at TFR to note defects. TFR noted in an interview during the study that bridge maintenance is often deferred and priority is given to the replacement of rail infrastructure (sleepers, ballast, tracks, etc.). The bridges were assessed for their current replacement cost and for the most cost effective bridge system as a replacement was also calculated.

7.1.2 The value of the bridge at any given time through its life cycle

SHMS, while capable of obtaining crucial information pertaining to defects on bridges, are still not being utilised as a replacement for the condition assessments of bridge structures in South Africa. From the bridge sample taken, shown in valuation reports on Tables 16-1 to 16-17 in Appendix A, the CRC, DRC and estimated sensor costs were calculated.

The sensor costs are assumed to include the installation and processing costs using wireless network sensors. The results were divided into three categories;

- The cost of 47.06% sensors are less than 90% of the DRC.
- The cost of 29.41% sensors make up 90 to 100% of the DRC.
- The cost of 23.53% sensors are more than the DRC.

More than three-quarters of the cost of sensors is either less than or equal to 100% of the Depreciated Replacement Cost. As stated in Chapter 2, the DRC is the portion of an asset's original cost that has already been written off as a depreciation expense in prior periods. DRC is a measure of the current value of an asset based on its current replacement cost less an allowance for deterioration of condition to date. This gives that if one of the bridges is to be replaced at any given time, the cost of installing sensors would be more cost effective than the bridge's depreciated value at the time of replacement. This aids in making the decision on whether to maintain a bridge or to renew it while keeping the bridge in a safe-to-use condition until it reaches its EUL. Therefore, there would be value in assessing the structure using SHMS and once installed using them for the continuous monitoring of the bridge for its RUL.

7.1.3 The current BMS versus using SHMS for monitoring

In a comparison between the current BMS which involves the routine maintenance of structures, it works out that the costs of SHMS are still considerably higher than the current means of conducting monitoring on bridges. However, once the technology is commercialised and is used on a lot more bridges the law of demand will result in a reduction in the costs of the unit.

Similar to the lifecycle model Figure 3-4 in Chapter 3, Setunge (2002) makes use of the flow chart shown in Figure 7-1, for the rehabilitation of bridge structures. The highlighted area amends the flow chart to eliminate the activities that will no longer form part of the rehabilitation process with the introduction of SHMS. With the information provided by the sensors they suggest the most suitable treatment options. Phase 4 does however require an asset manager to evaluate the treatment options and make a decision on the way forward, i.e. human intervention is required. With increased research into autonomous devices Phase 4 may also be eliminated in time. The fifth phase, not listed in the flowchart, is the allocation of resources for rehabilitation.

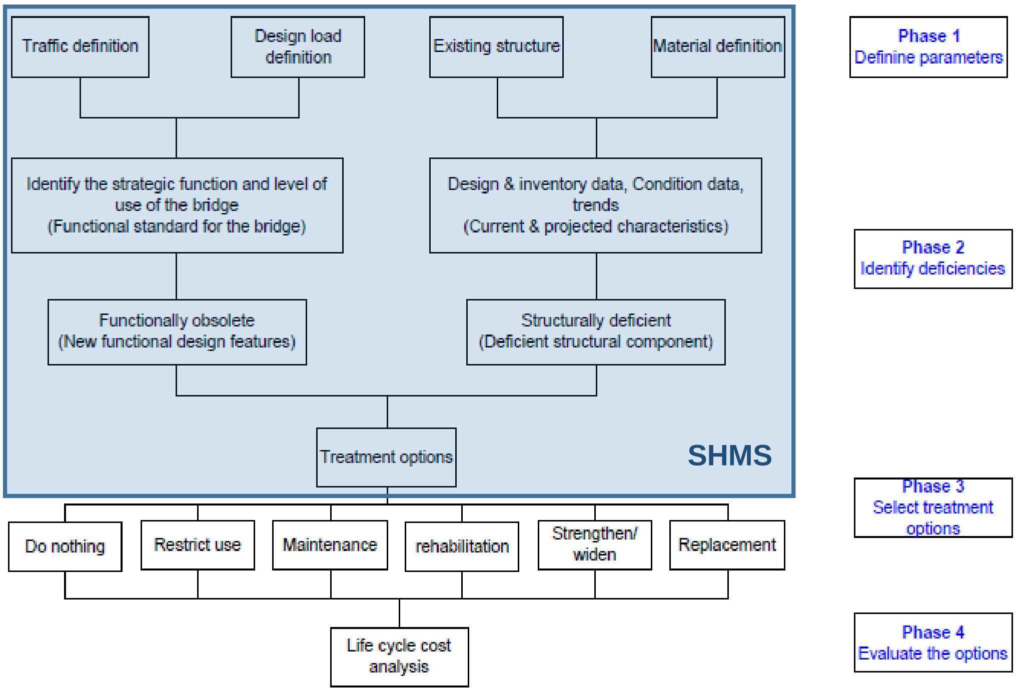


FIGURE 7-1: Flow-chart for the rehabilitation of bridge structures (Source: Setunge, 2002)

While it does indeed work out the SHMS are still not economically viable in South Africa (according to USA obtained costs of the systems), other factors that need to be taken into consideration are: The age gap discussed in Chapter 2 and the potential decline in costs in coming years as well as risk. The auxiliary benefits of mitigating the potential risks posed by not having SHMS installed may far outweigh the transient high cost of the sensors.

Where assets pose the greatest risk in the event of failure these assets should be considered as critical assets. Where:

Risk = Probability x Impact

There are various types of risks:

- Occupational Health and Safety, legal and compliance
- Financial, governance and security
- Environmental and business continuity
- Reputation, public liability and human resources.

In making decisions on critical assets such as bridges, aspects of the risks listed above fall within the framework of risks that need to be considered when deciding on a way forward for bridge monitoring. An oversight during a visual inspection on one of the TFR bridges for instance, may pose a safety risk, will result in financial losses, the income loss may affect TFR's bottom line, the reputation will be tarnished not only to clients (who will have to wait for their coal), but also in the event that there is a loss of life.

The risk management process entails: Setting the framework, identifying the risks, evaluating the risk and treating the risk in a process of continuous monitoring and reviewing (Mpofu, 2015). As part of the risk management framework certain criteria such as what is deemed as 'acceptable risk', needs to be identified. The risk evaluation criteria then need to be set i.e. looking at the probability of occurrence vs the consequences of failure. The cost of controls (using SHMS) vs the benefits may support the argument for value.

When considering critical assets, a uniform approach related solely to monetary terms cannot be adopted. The resultant consequences may come at a higher cost from loss of life, loss of income and a disruption in the level of service provision. Bridges, with the time they take to build, their construction costs and socio-economic and economic contributors to communities, should guide the discussion of the future of BMS in South Africa.

7.1.4 The future of BMS in South Africa

Heijll (2007) motivates for the continued development of CSHM methods in the future. Without CSHMS it will not be possible to assess old structures in an effective way and the cost for rebuilding will have an enormous impact on society. Hearn et al. (2000) shares the views of the challenges expressed in Chapter 2 about condition assessment methods which form the basis of current BMSs. As a result of this, the direction of BMS is seen to be moving towards a comprehensive approach to bridge management that focuses on the quantitative assessments of bridge performance and conditions rather than visual inspections and condition ratings. Hearn et al. (2000) also agree with Heijll (2007) for improved visual inspection procedures, innovative non-destructive testing methods; and automated methods to gather and manage data should be encouraged.

While it has been established that SHMS are currently not the most cost-effective means of bridge management in South Africa (SA), for countries like the United States of America (USA) these systems are almost compulsory. Hearn et al. (2000) reveal that the USA is currently experiencing a bridge crisis where the maintenance needs for older bridges have far outpaced available resources. The expense of data collection in the USA is higher than the cost of sensors and with the majority of bridge failures caused by unpredictable extreme weather events such as earthquakes and floods, there is economic value in implementing SHMS on their bridges. The lessons that can be learnt from the introduction of SHMS on USA bridges is to place a considerable emphasis on risk assessment.

SA has limited financial resources and a multitude of infrastructure needs and with the second largest economy in Africa is a major contributor to the economic development of Africa. It is therefore imperative that the infrastructure remains in a safe-to-use condition to avoid interruptions in the export of commodities and for the economic production of the country. The skills drain in the field of structural engineering may reach a stage where condition assessments are no longer viable. Thus the continued research into the economic value of using SHMS in SA is encouraged to explore wider aspects of value and risk mitigation.

7.2 Recommendations

Significant topics were identified during the research that warrant further investigation into this topic. These include:

- BMS and SHMS in the long term. The actual costs of BMS in the country. No statistical information was found on installers in the country.
- Looking at a longer study period
- A study on the validity of the life cycle models should be looked into using the real-time information obtained from SHMS.
- Using the lessons learnt from this study on railway bridges and determine to what extent it applies to road bridges.
- Value in the case study is limited to the economic importance of bridges such as those on the coal line in the micro economic sense. Socio-economic value has not been explored.
- Value in the study is also limited to the negative impact that BMS visual inspections will have on bridge management in the long term if SHMS are not installed.
- Maintenance records of the bridges could not be obtained, thus the condition is based on the expected condition for the respective ages of the bridges and the service life cycle models. The research can be refined by using the actual condition of the structures and a direct comparative study can be made between BMS and SHMS. This study should also contain the actual construction costs of the bridges.

REFERENCES

1. Balgeas, D. 2006. *Introduction to Structural Health Monitoring*. In: Edition 1. Balgeas, D., Fritzen, C and Guemes, A. Edition 1. 2006. Structural Health Monitoring. Published by: ISTE. Place: Bordeux, France. Pp. 13 – 43.
2. Beushausen, H. *Assessment of Concrete Structures* lecture notes from course CIV5116Z presented in 2015 at The University of Cape Town. (Lectures presented 29 June – 3 July 2015).
3. Boshoff, L., Cartwright, A., Coovadia, Y., Fani, L., Graham, N., Hunter, R., Palmer, I., Viljoen, J., Walsh, K and Welgemoed, W. 2013. *2013 South African Cities Network. State of city finances report*. Available at: www.sacities.net.
4. Busatta, F and Moyo, P and Alexander, M.G. 2015. Vibration monitoring of a large scale heavy haul railway viaduct.
5. Büyüköztürk, O. 2007. *Higher tech bridge inspections*. MIT Technology review.
6. Fifth National Conference on Earthquake Engineering, 26-30 May 2003, Istanbul, Turkey Paper No: Büyüköztürk, O. and Yu, *T. Structural Health Monitoring and seismic impact assessment.* 2003.
7. Center for Automotive Research (CAR) and Michigan Tech. 2012. Economic evaluation of commercial remote sensors for bridge health monitoring.
8. Chen, B., Wang, X., Sun, D. and Xie, X. 2014. *Integrated system of Structural Health Monitoring and Intelligent Management for a cable-stayed bridge*. The Scientific World Journal - Volume 2014, Article ID 689471. Available at: http://ezproxy.uct.ac.za.
9. Committee of Transport Officials: South Africa. 2016. Technical Methods for Highways (TMH 19) – Manual for the visual assessment of road structures – Part A: *Road structure management information.* 2016.
10. Committee of Transport Officials: South Africa. 2016. Technical Methods for Highways (TMH 19) – Manual for the visual assessment of road structures – Part B: *Visual assessment guide.* 2016.
11. Committee of Transport Officials: South Africa. 2016. Technical Methods for Highways (TMH 22) – Part C: *Road assessment management manual.* 2013.
12. Dalton, S., Atamturktur, S. and Juang, H. 2013. Structural Health Monitoring for sustainable and resilient infrastructure management. Clemson University, South Carolina.

13. Derriso, M.M., DeSimio, M.P., McCurry, C.D., Schubert Kabban, C.M. and Olson, S.E. 2014. *Industrial evaluation to information age structural health monitoring*. Sage Journals. Available at: www.jourmals.sagepub.com.
14. Dhillon, B.S. 2009. *Life cycle costing for engineers*. Boca Raton, Florida. CRC Press Publishers.
15. Dudley, B. 2016. BP Statistical review of world energy: June 2015.
16. Du Toit, H.J.L. 1976. The Broodsnyersplaas – *Richards Bay railway line and harbour: Overall objectives, features, planning process and constraints*. Die Siviele Ingenieur in Suid Afrika – November 1976, P. 245.
17. U.S. Department of Transportation: Federal Highway Administration. 2011. *Framework for improving resilience of bridge design*. Publication no. FHWA-IF-11-016. Available at: www.fhwa.dot.gov.
18. Fourie, J. 2006. *Some policy proposals for future infrastructure investment in South Africa. Stellenbosch Economic Working Papers: 2005-2006*. University of Stellenbosch.
19. Green, A., 2009. Introducing the New Standards for Life Cycle Costing in Construction. *Stockholm Conference*. 27 November 2009. Sweden.
20. Guba, E.G. and Lincoln, Y.S. 1981. *Effective evaluation*.
21. Haardt, P and Holst, R. 2008. *The German approach to bridge management – Current Status and Future Development.* In: Transport Research Circular: International Bridge and structure management. 10th international conference on bridge and structure management. 20-22 October 2008. Buffalo, New York.
22. Hearn, G. 2007. National Cooperative Highway Research: *Bridge inspection practices*. Transportation research board.
23. Hearn, G., Purvin .R.L., Thompson, P., Bushman, W.H. Mc Ghee, K.K. McKeel Jr., W.T. 2000. *Bridge Maintenance and Management: A look to the future*. Transportation Research Board. Editor of book. Surname, Initials. 2000. Title of Book. Published where.
24. Hejll, A. 2007. Civil Structural Health Monitoring: Strategies, Methods and Applications, 2007. PHD. Luleå University of Technology
25. Helmstadter, G.C. 1970. *Research concepts in human behaviour: Education, Psychology, Sociology*.
26. Hurlebaus, S., Stocks, T., and Ozbulut, O.E. 2014. *Smart structures in engineering education*. Texas A&M University, College Station.

27. Humphries, S. 2013. 8 *SANRAL Case Studies* – Lecture notes from Bridge Management course presented by S. Humphries in 2013 at The University of Cape Town.
28. Institute of Municipal Engineering of Southern Africa (IMESA). 2011. *Quick guide to the international infrastructure management manual (International Edition).*
29. Inaudi, D. 2011. 5th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-5) 2011. *Cost-benefit analysis in SHM Projects*. 11-15 December 2011, Cancún, México.
30. Kalantari, M and Mirbaghen, A. 2012. State Highway Administration research report - *Low cost Structural Health Monitoring of bridges using wireless senspot sensors*.
31. Kessides, C. 1993. The contributions of infrastructure to economic development.
32. Kruger, E and Humphries, S. 2008. Presentation on *Repair of Bridge IB42 over the Limpopo River at Stockpoort border post.* Presented at the University of Cape Town for Bridge Management course.
33. Kuys, W. 2011. *Transnet: Heavy haul operations in South Africa – IHHA 2011*. Available at: www.ihha.net.
34. Lallart, M., Monnier, T. and Guyomar, D. 2010. *Energy-efficient method for embedded in situ structural health monitoring*. Universite´ de Lyon, Villeurbanne, France. Available at: http://ezproxy.uct.ac.za.
35. Maree, K. 2007. *First steps in research*. Revised Edition. Pretoria, South Africa: Van Schaik publishers.
36. Mbanjwa, T. 2014. An investigation of the relationships between inventory and inspection data of RC bridges and RC culverts in the Western Cape Province. University of Cape Town.
37. Mc Donald, I. 2013. Overview of Cape Town's Bridge Management System and challenges facing the city.
38. Mohr, P., Fourie, L. and associates. 2008. *Economics for South African students*. 4th edition. Pretoria, South Africa: Van Schaik publishers.
39. Moyo, P and Alexander, M.G. 2006.Condition assessment of bridges in South Africa: Challenges and opportunities.
40. National Treasury. 2003. *Local Government Capital Asset Management Guideline*; (Chapter 6). Municipal Finance Management Act: 2003. South Africa: National Treasury.

41. National Treasury. 2012*. Accounting Guideline for GRAP 17: Property, Plant and Equipment.* Available at: https://oag.treasury.gov.za/Publications. Accessed: [14 February 2017]

42. Pellissier, R. 2007. *Business research made easy*. Cape Town, South Africa. Juta publishers.

43. Perkins, P. 2011. The role of economic infrastructure in economic growth: building on experience.

44. Quick, D. 2011. Wireless sensor to monitor structural integrity of bridges.

45. Railway Gazette. 2013. *Transnet to expand heavy haul operations*. Available at: http://www.railwaygazette.com

46. Rice, J.A. and Spencer, 2009. B.F. *Flexible smart sensor framework for autonomous full scale Structural Health Monitoring.* NSEL Report Series: Report No. NSEL-018. August 2009. University of Illinois at Urbana – Champaign.

47. Richards Bay Coal Terminal (RBCT). Available at: www.rbct.co.za.

48. Roux, M.P., Nordengen, P.A., Tekie, S.B. and Rittmann, R. 2010. *The Namibia Bridge Management System: A tool for preservation of structures on the road network*. Pretoria South Africa. Council for Scientific and Industrial Research.

49. Rust, F.C. and Koen, R. 2011. *Positioning technology development in the South African construction industry: A technological foresight.* Journal of the South African Institution of Civil Engineering. Online version ISSN 2309-8775. Available at: www.scielo.org.za.

50. Ryall, M.J. 2010. *Bridge Management. 2nd edition*. Jordan Hill, Oxford. Butterworth Heinemann Publishers.

51. South African Institution of Civil Engineering. 2011. *SAICE infrastructure report card for South Africa*. Available at: www.saice.org.za.

52. South African National Roads Agency Limited – *Bridge Management System*.

53. South African Reserve Bank. 2012. *Budget review* 2012.

54. Setunge, S. et al. 2002. *Whole of Life Cycle cost analysis in bridge rehabilitation*. Report 2002-055-C-003. Available at: www.construction-innovation.info.

55. Shaffer, J.K. and Schellhase, M.C. 2008. *International Bridge and Structure Management: Integrated Management and Inspection System for Maryland Counties and Cities.* In: Transport Research Circular: International Bridge and structure management. 10th international conference on bridge and structure management. 20-22 October 2008. Buffalo, New York.

56. Spencer, B.F. 2013.*Structural Health Monitoring of civil infrastructure from research to practice.* CSIC Seminar Professor Bill Spencer presentation. University of Illinois. Available at: www.yumpu.com
57. Statistics South Africa. 2014. *Statistical Release: Gross Domestic Product – P0441.* Available at: www.statssa.gov.za
58. Stewart, M.G. 2001. *Reliability-based assessment of ageing bridges using risk-ranking and life cycle cost decision analyses*. Reliability Engineering and System Safety, Vol. 74.
59. Transnet Freight Rail. 2015. *Long term planning framework – Rail development plan*. Available at: www.transnet.net.
60. Transnet Freight Rail: Rothman, H.W., Van den Berg, J., Vosloo, J., Botha, D., and Homan, J. 2010. *Infrastructure engineering: Manual for Infrastructure Condition Assessment (MICA)* – 16 August 2010. [**Confidential Internal Transnet document**].
61. The White House National Economic Council (NEC). 2014. The Economic analysis of transportation infrastructure investment.
62. Tripathi, N. et al. 2016. *Reclamation of mine – impacted land for ecosystem recovery*.
63. Van der Wegen, G., Polder, R.B. and Van Breugel, K. 2012. *Guideline for service life design of structural concrete - A performance based approach with regard to chloride induced corrosion*. Delft University of Technology, Netherlands.
64. Wall, K. 2011. Financial Mail: *Jobs for life*. 27 May 2011.
65. Ward, B. 2016. *Ultrasonic inspection approaches for measuring corrosion wall loss in process piping*. Quality Magazine: www.qualitymag.com
66. Wardhana, K and Hadipriono, F.C. 2003. *Analysis of recent bridge failures in the United States*. Journal of performance of constructed facilities – Vol. 17, No. 3, 1 August 2003, P. 144.
67. Zhou, G and Yi, T. 2013. *Recent Developments on Wireless Sensor Networks Technology for Bridge Health Monitoring*.

APPENDIX A

List of valuation reports

TABLE 15-1: Valuation Report 1.

Line Section	Piet Retief - Sikame
Bridge/Length	Rail/Road RC Bridge (1972) – 15.15m
Lines at Bridge	2 No.
CRC	R 3 022 500.00
DRC	R 1 360 125.00
AGE	44
Sensors Alternative	152 sensors at $600/sensor (exchange rate of R13.50) = R 8 100.
Sensor Cost	R 1 231 200.00
Valuation Report	Sensors make up 40.7% of the Current Replacement Cost of this Bridge and 91% of the Depreciated Replacement Cost.

TABLE 15-2: Valuation Report 2.

Line Section	Piet Retief - Sikame
Bridge/Length	Road over Rail RC Bridge (1975) – 35.78m
Lines at Bridge	2 No.
CRC	R 14 276 400.00
DRC	R 6 959 745.00
AGE	41
Sensors Alternative	400 sensors at $600/sensor (exchange rate of R13.50) = R 8 100.
Sensor Cost	R 3 240 000.00
Valuation Report	Sensors make up 22.7% of the Current Replacement Cost of this Bridge and 46.5% of the Depreciated Replacement Cost.

TABLE 15-3: Valuation Report 3.

Line Section	Piet Retief - Sikame
Bridge/Length	RC Viaduct (1972) – 480.00m
Lines at Bridge	2 No.
CRC	R 191 520 000.00
DRC	R 86 184 000.00
AGE	44
Sensors Alternative	5000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100.
Sensor Cost	R 40 500 000.00
Valuation Report	Sensors make up 21.15% of the Current Replacement Cost of this Bridge and 46.99% of the Depreciated Replacement Cost.

TABLE 15-4: Valuation Report 4.

Line Section	Piet Retief - Sikame
Bridge/Length	RC Viaduct (1972) – 165.00m
Lines at Bridge	2 No.
CRC	R 65 835 000.00
DRC	R 29 625 750.00
AGE	44
Sensors Alternative	2000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100.
Sensor Cost	R 16 200 000.00
Valuation Report	Sensors make up 24.61% of the Current Replacement Cost of this Bridge and 54.68% of the Depreciated Replacement Cost.

TABLE 15-5: Valuation Report 5.

Line Section	Piet Retief - Sikame
Bridge/Length	RC Viaduct (1984) – 400.00m
Lines at Bridge	1 No.
CRC	R 79 800 000.00
DRC	R 32 917 500.00
AGE	33
Sensors Alternative	4000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100.
Sensor Cost	R 32 400 000.00
Valuation Report	Sensors make up 40.6% of the Current Replacement Cost of this Bridge and 98.43% of the Depreciated Replacement Cost.

TABLE 15-6: Valuation Report 6.

Line Section	Sikame – Vryheid East
Bridge/Length	Open ribbed Spandrel (1968) – 109.73m
Lines at Bridge	2 No.
CRC	R 43 782 000.00
DRC	R 17 512 800.00
AGE	48
Sensors Alternative	1500 sensors at $600/sensor (exchange rate of R13.50) = R 8 100.
Sensor Cost	R12 150 000.00
Valuation Report	Sensors make up 27.75% of the Current Replacement Cost of this Bridge and 69.3% of the Depreciated Replacement Cost.

TABLE 15-7: Valuation Report 7.

Line Section	Sikame – Vryheid East
Bridge/Length	Rail over Road RC Bridge (1969) – 15.40m
Lines at Bridge	2 No.
CRC	R 3 072 300.00
DRC	R 1 267 323.75
AGE	47
Sensors Alternative	150 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 1 215 000.00
Valuation Report	Sensors make up 39.55% of the Current Replacement Cost of this Bridge and 95.87% of the Depreciated Replacement Cost.

TABLE 15-8: Valuation Report 8.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	OH Road Bridge (1969) – 35.66m
Lines at Bridge	1 No.
CRC	R 7 114 200.00
DRC	R 2 934 607.50
AGE	47
Sensors Alternative	400 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 3 240 000.00
Valuation Report	Sensors make up 45.54% of the Current Replacement Cost of this Bridge and 110.41% of the Depreciated Replacement Cost.

TABLE 15-9: Valuation Report 9.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Arched Bridge (1969) – 130.45m
Lines at Bridge	1 No.
CRC	R 26 024 700.00
DRC	R 10 735 188.75
AGE	47
Sensors Alternative	1500 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 12 150 000.00
Valuation Report	Sensors make up 46.69% of the Current Replacement Cost of this Bridge and 113.18% of the Depreciated Replacement Cost.

TABLE 15-10: Valuation Report 10.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Bridge (1969) – 99.06m
Lines at Bridge	1 No.
CRC	R 19 762 500.00
DRC	R 8 152 031.25
AGE	47
Sensors Alternative	1000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 8 100 000.00
Valuation Report	Sensors make up 40.99% of the Current Replacement Cost of this Bridge and 99.36% of the Depreciated Replacement Cost.

TABLE 15-11: Valuation Report 11.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Arched Bridge (1985) – 603.50m
Lines at Bridge	1 No.
CRC	R 120 398 400.00
DRC	R 72 239 040.00
AGE	32
Sensors Alternative	6000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100 **Cost of units is reduced over 10 000 units.
Sensor Cost	R 48 600 000.00
Valuation Report	Sensors make up 40.37% of the Current Replacement Cost of this Bridge and 67.28% of the Depreciated Replacement Cost.

TABLE 15-12: Valuation Report 12.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Arched Bridge (1970) – 259.69m
Lines at Bridge	1 No.
CRC	R 51 808 200.00
DRC	R 22 018 485.00
AGE	46
Sensors Alternative	3000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 24 300 000.00
Valuation Report	Sensors make up 46.9% of the Current Replacement Cost of this Bridge and 110.36% of the Depreciated Replacement Cost.

TABLE 15-13: Valuation Report 13.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Arched Bridge (1987) – 110.00m
Lines at Bridge	1 No.
CRC	R 21 945 000.00
DRC	R 13 715 625.00
AGE	30
Sensors Alternative	1500 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 12 150 000.00
Valuation Report	Sensors make up 55.37% of the Current Replacement Cost of this Bridge and 88.59% of the Depreciated Replacement Cost.

TABLE 15-14: Valuation Report 14.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Arched Bridge (1970) – 152.40m
Lines at Bridge	1 No.
CRC	R 30 403 800.00
DRC	R 12 921 615.00
AGE	46
Sensors Alternative	2000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 16 200 000.00
Valuation Report	Sensors make up 53.28% of the Current Replacement Cost of this Bridge and 125.37% of the Depreciated Replacement Cost.

TABLE 15-15: Valuation Report 15.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Bridge (1976) – 164.50m
Lines at Bridge	1 No.
CRC	R 32 817 900.00
DRC	R 16 408 950.00
AGE	40
Sensors Alternative	2000 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 16 200 000.00
Valuation Report	Sensors make up 49.36% of the Current Replacement Cost of this Bridge and 98.72% of the Depreciated Replacement Cost.

TABLE 15-16: Valuation Report 16.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge/Length	RC Bridge (1976) – 120.00m
Lines at Bridge	1 No.
CRC	R 23 940 000.00
DRC	R 11 970 000.00
AGE	40
Sensors Alternative	1200 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 9 720 000.00
Valuation Report	Sensors make up 40.6% of the Current Replacement Cost of this Bridge and 81.2% of the Depreciated Replacement Cost.

TABLE 15-17: Valuation Report 17.

Line Section	Vryheid East – Richards Bay Coal Terminal
Bridge	RC Bridge (1976) – 119.05m
Lines at Bridge	1 No.
CRC	R 23 750 400.00
DRC	R 11 875 200.00
AGE	40
Sensors Alternative	1200 sensors at $600/sensor (exchange rate of R13.50) = R 8 100
Sensor Cost	R 9 720 000.00
Valuation Report	Sensors make up 40.93% of the Current Replacement Cost of this Bridge and 81.8% of the Depreciated Replacement Cost.

APPENDIX B

Transnet Railway infrastructure asset condition assessment for concrete bridges: BBC 8226

RAILWAY INFRASTRUCTURE ASSET

CONDITION ASSESEMENT DOCUMENT

TRANSNET
Freight rail

CONCRETE BRIDGES ***MICA REF.: BBC 8226 (4.1.1)***

Name/ Description				Depot	
Station to Station					
Nearest Station		Plan Section No.		Plan km	
Inspected By		Functional Location			
Employee No.		Centroid (Lat)		Date	
Designation		Centroid (Lon)			
Inspection Type		Span (No/L)		Height	m
Signature		Bridge Type			
		Deck Type		Length	m

		N/A	U/I	1	2	3	4	Comments	M
Abutment and Foundation	C1								
Bearing	C2								
Retaining Wall and Foundation	C3								
Pier Protection Works	C4								
Pier, Columns and Foundation	C5								
Waterway	C6								
Longitudinal Member	C7								
Transversal Member	C8								
Deck Slab	C9								
Deck Slab Drainage	C10								
Embankment Protection Works	C11								
Approach Surface	C12								
Guardrail (Road)	C13								
Parapet/Handrailing	C14								
Deck Surfacing	C15								
Kerb/Side Walk	C16								
Expansion Joint	C17								
Miscellaneous	C18								
Track : Geometry	C19								
Rail	C20								
Fastening	C21								
Sleeper	C22								
Ballast	C23								
Vertical clearance sign	C24								

Line Importance/Income	BI 1	High	Medium	Low
Detour Length	BI 2	200 km	20 km	Zero
Structure Usage	BI 3	Daily	Weekly	Not in use
Corrosion Factor	BI 4	Severe	Normal	Low
Access to Site	BI 5	Difficult	Fair	Easy
Replacement Complexity	BI 6	High	Medium	Easy
Design Life Cycle	BI 7	End of life	Halfway	New
Environmental Impact	BI 8	High Risk	Medium	Low Risk

Legend:

N/A	This item does not exist
U/I	Unable to inspect this item
1	Good; N/A; U/I
2	Minor repairs. Ignore
3	Planned Maintenance
4	Immediate/Emergency repair work
M	To be monitored. Show period

RRV Inspection Required	Yes	No
Refer to Bridge Office	Yes	No
Budget	Yes	No

Photo's taken

	Remarks	Signature
Maintenance Manager		
Depot Engineer		
Senior Engineer, Bridges		

Available on ProjectWise under document number BBC 8226

APPENDIX C

Correspondence with Transnet Freight Rail

Gmail | Kea M <ammekwa@gmail.com>

FW: Bridge Monitoring (Required Information)

Keamogetswe Mmekwa <ammekwa@gmail.com> | Fri, Nov 25, 2016 at 12:03 PM
To: Mutshinya Netshidzati Transnet Freight Rail PTA <Mutshinya.Netshidzati@transnet.net>

Hi Mutshinya
You can edit to suit, but here's the info rewritten, thanks so much for your effort.

We are looking for information on the Ermelo to Richards Bay line (Coal line). The information required on the line:

- The profile of the line from Ermelo to Richards Bay, showing all the bridges on the line, deviations/where the line splits.
- What are the costs associated with closing of the bridge, be it for maintenance or forced closure (if any, unless there are alternative routes).
- Frequency of use (assumed that the line is operational 24 hours)
- What type of bridges are on the line: Confirm if there are any steel bridges on the line. If all concrete what type of bridges are there (how many bridges are on the line): eg. are they Arch bridges, voided, box girders etc.
- Do we have dates on how old these bridges are?
- How often are the bridges inspected for defects?
- What types of structural inspections are conducted, is it doen according to a some management system e.g. SANRAL's BMS (Bridge Management)
- and lastly, is there any form of structural health monitoring being conducted on any of the bridges?

(To answer Petros) The information is required asap.

Regards,